Physical versus economic water footprints in crop production: a case study for China

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10 Abstract

A core goal of sustainable agricultural water resources management is to implement lower water footprint (WF), i.e., higher 11 12 water productivity, while maximising economic benefits in crop production. However, previous studies mostly focused on 13 crop water productivity from a single physical perspective. Little attention is paid to synergies and trade-offs between water 14 consumption and economic value creation of crop production. Distinguishing between blue and green water composition, grain 15 and cash crops, and irrigation and rainfed production modes in China, this study calculates the production-based WF (PWF) and derives the economic value-based WF (EWF) of 14 major crops in 31 provinces for each year over 2001-2016. The 16 17 synergy evaluation index (SI) of PWF and EWF is proposed to evaluate quantitatively the synergies and trade-offs between 18 the two. Results show that both the PWF and EWF of most considered crops in China decreased with the increase of crop yield 19 and prices. The high (low) values of both PWF and EWF of grain crop tended to obvious cluster in space and there existed a 20 huge difference between blue and green water in economic value creation. Moreover, the SI revealed a serious incongruity 21 between PWFs and EWFs both in grain and cash crops. Negative SI values occurred mostly in northwest China for grain crops, 22 and overall more often and with lower values for cash crops. Unreasonable regional planting structure and crop prices resulted 23 in this incongruity, suggesting the need to promote regional coordinated development to adjust the planting structure according 24 to local conditions and to regulate crop prices rationally.

25 1 Introduction

Humanity is facing the increasingly severe threat of water shortage and accompanying rising food risks (Mekonnen and Hoekstra, 2016; Veldkamp et al., 2017), posing great challenges to agricultural water resource management. The economic benefits of water use form one important pillar of fresh water distribution (Hoekstra, 2014). However, traditional studies on agricultural efficient water use focus on crop water productivity from the physical perspective, and rarely make comprehensive

evaluations combining the results with an economic perspective. The water footprint (WF) (Hoekstra, 2003) reveals the 30 31 consumption and pollution of water in the process of production or consumption and assesses fresh water appropriation in its 32 entirety (Hoekstra et al., 2011). The consumptive WF of crop production can be divided into blue and green WFs (Hoekstra et 33 al., 2011). Blue water is surface and ground water, whereas green water is defined as the water kept in the unsaturated soil 34 layer and precipitation, which is eventually transferred into canopy evapotranspiration (Falkenmark and Rockstrom, 2006). In 35 agriculture, the blue WF measures irrigation water consumption. Green WF refers to the consumption of rainwater (Hoekstra et al., 2011). As comprehensive index to evaluate types, quantities, and efficiency of water use in the process of crop production, 36 the WF of crop production can be expressed based on both production (PWF, m³ kg⁻¹) and economic value (EWF, m³ per 37 38 monetary unit) (Garrido et al., 2010; Hoekstra et al., 2011), which unifies the measurement of the physical and economic levels. 39 PWF and EWF provide clear insights for reducing the water resources input for harvesting crop yields and optimizing the 40 economic benefits per unit of water consumption, respectively.

Garrido et al. (2010) firstly evaluated WF in terms of m³ \in ¹, from a perspective of hydrology and economy for agricultural 41 42 production of Spain. They found that in areas where blue water was scarce but dominant in crop production, the scarce blue 43 water resource was used to irrigate high-value crops, thus achieving higher yields and economic benefits, with a more efficient 44 blue water utilisation with increasing scarcity. In a case study for Kenya, Mekonnen and Hoekstra (2014a) encouraged to use 45 domestic water resource for production of the rainfed cash crops with high economic benefits, rather than for water-intensive export commodities with low economic benefits. Schyns and Hoekstra (2014) found that water and land resources in Morocco 46 were mainly used to produce export crops with relatively low economic value (in terms of USD m⁻³ and USD ha⁻¹), and that 47 water-scarce countries should attribute great importance to the allocation of freshwater and adjust crop planting structure from 48 49 the perspective of economic efficiency. Chouchane et al. (2015) quantified the WF in Tunisia and evaluated the blue and green 50 economic water productivity and economic land productivity in irrigation and rainfed agriculture from an economic 51 perspective. They showed that irrigation water was not generally used to increase economic water productivity (USD m⁻³) but 52 rather to increase economic land productivity (USD ha⁻¹), so it would be advantageous to expand the irrigated area of crops 53 with high economic water productivity. Furthermore, in recent years, there have been studies on the dairy industry (Owusu-54 Sekyere et al., 2017a; Owusu-Sekyere et al., 2017b), the meat industry (Ibidhi and Salem, 2018) and the wine industry 55 (Miglietta et al., 2018) to explore the WF assessment combined with an economic perspective.

Nevertheless, the above studies lacked a complete temporal and spatial evolution analysis of the WF from the economic perspective. More importantly, the above studies did not involve the study of WF coordination in different aspects, which means a good synergy in reducing the water resources input for harvesting crop yields and optimizing the economic benefits per unit of water consumption, compared with national average level. Thus, the synergies and trade-offs between water consumption and economic value creation during crop production in WF assessment, which is undoubtedly of great significance, are ignored. 62 Scientifically planning agricultural water resource utilisation and balancing crop production, water consumption and social 63 economic development are severe challenges faced by all humankind. However, China, with millions of small farmers led by 64 smallholder production, has become one of the regions facing the biggest challenges (Tilman et al., 2011; Gao and Bryan, 65 2017; Cui et al., 2018). Being the country with the largest population and food consumption, China faces a series of problems, 66 such as extensive management and low utilisation rate of water resource in agricultural production (Khan et al., 2009; Kang 67 et al., 2017). Previous studies on China have quantified the WF of crop production at the irrigation district scale (Sun et al., 68 2013; Cao et al., 2014; Sun et al., 2017), watershed scale (Zhuo et al., 2014; Zhuo et al., 2016c) and national scale (Zhuo et al., 2017) 69 al., 2016b; Wang et al., 2019). Sun et al. (2013) found that the WF of crop depended on agricultural management rather than 70 on regional climate differences; Zhuo et al. (2016b) showed that China's domestic food trade was determined by the economy 71 and government policies, not by regional differences in water endowments; Wang et al. (2019) showed possibility and 72 importance of accounting for developments of water-saving techniques in largescale crop WF estimations. However, most of 73 these studies focused on quantifying WF from a single physical perspective. To our knowledge, there is no study yet to provide 74 clear insights into the economic benefits of water use.

75 To fill the above research gap, the current study objective is, taking China over 2001-2016 as the study case, to explore the 76 relationship between water resource consumption and economic value creation of intra-national scale crop production, and to 77 propose a synergy evaluation index (SI) of PWF and EWF. First, the blue and green PWF (PWF_b, PWF_g) of 14 major crops 78 (winter wheat, spring wheat, spring maize, summer maize, rice, soybean, cotton, groundnut, rapeseed, sugar beet, sugarcane, 79 citrus, apple, and tobacco) is calculated annually in 31 provinces at the meteorological station level, and the corresponding 80 EWF is derived. Table 1 shows the number of meteorological stations per province. Second, crops are distinguished between 81 grain and cash crops, with Mann-Kendall trend test and spatial autocorrelation analysis method for evaluation of the temporal 82 and spatial evolution characteristics of PWF and EWF. Finally, the synergy evaluation index (SI) is constructed to reveal the 83 synergies and trade-offs of crop water productivity and its economic value from the WF perspective. Consequently, based on 84 the quantification of PWF and EWF, we constructed the synergy evaluation index (SI) of water footprint, so that the original 85 intention of the study -- comprehensive assessment from the perspective of both physics and economics can be implemented.

86

87 Table 1. Number of meteorological stations per province.

89 2 Method and data

90 2.1 AquaCrop modeling

91 Crop WF per unit mass is defined by the evapotranspiration (ET) and yield (Y) over the growing period (Hoekstra et al., 2011).
92 The AquaCrop model (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009), a water driven crop water productivity model
93 developed by FAO, is used to simulate the daily green and blue ET and yield Y of 14 crops for each station. The AquaCrop
94 has fewer parameters than other crop growth models and provides a better balance between simplicity, accuracy, and robustness
95 (Steduto et al., 2009). A large number of studies have demonstrated the good performance of AquaCrop in simulating crop
96 growth and water use under different environmental conditions (Abedinpour et al., 2012; Jin et al., 2014; Kumar et al., 2014).
97 Also, there have been a number of studies using AquaCrop to calculate water footprints (Chukalla et al., 2015; Zhuo et al.,

98 2016a; Zhuo et al., 2016c; Wang et al., 2019). The dynamic soil water balance in the AquaCrop model is shown in Eq. (1):

99
$$S_{[t]} = S_{[t-1]} + PR_{[t]} + IRR_{[t]} + CR_{[t]} - ET_{[t]} - RO_{[t]} - DP_{[t]},$$
(1)

where $S_{[t]}$ (mm) is the soil moisture content at the end of day t; $PR_{[t]}$ (mm) is the rainfall on day t; $IRR_{[t]}$ (mm) is the irrigation amount on day t; $CR_{[t]}$ (mm) is the capillary rise from groundwater; $RO_{[t]}$ (mm) is the surface runoff generated by rainfall and irrigation on day t; $DP_{[t]}$ (mm) is the amount of deep percolation on day t. $RO_{[t]}$ is obtained through the Soil Conservation Service curve-number equation (USDA, 1964; Rallison, 1980; Steenhuis et al., 1995):

104
$$RO_{[t]} = \frac{(PR_{[t]} - I_a)^2}{PR_{[t]} + S - I_a},$$
 (2)

where S (mm) is the maximum potential storage, which is a function of the soil curve number; I_a (mm) is the initial water loss before surface runoff; $DP_{[t]}$ (mm) is determined by the drainage capacity (m³ m⁻³ day⁻¹). When the soil water content is less than or equal to the field capacity, the drainage capacity is zero (Raes et al., 2017).

AquaCrop model is able to track the daily inflow and outflow at the root zone boundary. On this basis, we use the blue and green WF calculation framework by Chukalla et al. (2015), Zhuo et al. (2016c) and Hoekstra (2019) combined with the model of soil water dynamic balance to separate the daily blue and green ET (mm), as shown in Eqs. (3) and (4):

111
$$S_{b[t]} = S_{b[t-1]} + IRR_{[t]} - RO_{[t]} \times \frac{IRR_{[t]}}{PR_{[t]} + IRR_{[t]}} - (DP_{[t]} + ET_{[t]}) \times \frac{S_{b[t-1]}}{S_{[t-1]}},$$
(3)

112
$$S_{g[t]} = S_{g[t-1]} + PR_{[t]} - RO_{[t]} \times \frac{PR_{[t]}}{PR_{[t]} + IRR_{[t]}} - (DP_{[t]} + ET_{[t]}) \times \frac{S_{g[t-1]}}{S_{[t-1]}},$$
(4)

- 113 where S_{b[t]} and S_{g[t]} (mm) respectively represent the blue and green soil water content at the end of day t. According to Siebert
- 114 and Döll (2010), the maximum soil moisture of rainfed fallow land two years before planting is taken as the initial soil moisture
- 115 for simulating. At the same time, the initial soil water during the growing period is set as green water (Zhuo et al., 2016c).
- 116 The blue and green components in DP and ET were calculated per day based on the fractions of blue and green water in the
- 117 total soil water content at the end of the previous day (Zhuo et al., 2016a), which are shown in Eqs. (5) and (6):

118
$$ET_{b[t]} = ET_{[t]} \times \frac{S_{b[t-1]}}{S_{[t-1]}},$$
 (5)

119
$$ET_{g[t]} = ET_{[t]} \times \frac{S_{g[t-1]}}{S_{[t-1]}},$$
 (6)

Using the normalized biomass water productivity (WP*, kg m⁻²), which is normalized for the atmospheric carbon dioxide (CO₂) concentration, the evaporative demand of the atmosphere (ET₀) and crop classes (C3 or C4 crops), AquaCrop calculates daily aboveground biomass production (B, kg) from daily transpiration (Tr) and the corresponding daily reference evapotranspiration (ET₀) (Steduto et al., 2009):

124
$$B = WP * \sum \frac{T_{r[t]}}{ET_{0[t]}}$$
 (7)

The crop yield (harvested biomass) is the product of the above-ground biomass (B) and the adjusted reference harvest index
(HI₀, %) (Raes et al., 2017).

$$127 \quad Y = f_{HI} H I_0 B \,, \tag{8}$$

where the adjustment factor(f_{HI}) reflects the water and temperature stress depending on the timing and extent during the crop cycle.

130 **2.2 Calculation of production-based water footprint (PWF)**

131 The PWF (m³ kg⁻¹) consists of the blue PWF (PWF_b, m³ kg⁻¹) and the green PWF (PWF_g, m³ kg⁻¹), which are respectively

- 132 calculated from the daily blue evapotranspiration (ET_{b[t]}, mm) and daily green evapotranspiration (ET_{g[t]}, mm) and crop yield
- 133 (Y, kg ha⁻¹) during the growing period (Hoekstra et al., 2011), as shown in Eqs. (9) (11):

$$134 \quad PWF = PWF_b + PWF_g, \tag{9}$$

135
$$PWF_b = \frac{10 \times \sum_{t=1}^{gp} ET_{b[t]}}{Y},$$
 (10)

136
$$PWF_g = \frac{10 \times \sum_{t=1}^{gp} ET_{g[t]}}{Y},$$
 (11)

where gp (day) is the length of growing period; 10 is the conversion coefficient. The daily ET and Y values during the growth period are simulated by the AquaCrop model. Being consistent with the existing calibration method which has been widely applied (Mekonnen and Hoekstra, 2011; Zhuo et al., 2016b; Zhuo et al., 2016c; Wang et al., 2019; Zhuo et al., 2019), the modeled crop yield was calibrated at provincial level according to the statistics (NBSC, 2019). Within a province, we calibrated the average level of the modeled yields among station points to match the provincial statistics. Therefore, we kept the spatial variation in crop yields, so that in associated water footprints simulated by AquaCrop model.

143 2.3 Calculation of economic value-based water footprint (EWF)

Following Hoekstra et al. (2011), the EWF (m³ USD⁻¹) of crop production represents the water consumption per unit of economic value.

146
$$EWF = \frac{PWF}{UP}$$
, (12)

where PWF (m³ kg⁻¹) the production-based WF, and UP (USD kg⁻¹) the crop unit price. The economic benefit unit refers to crop price in the current study. The EWF is numerically equal to the inverse of the economic water productivity. Considering the PWF and the EWF together provides a clear and intuitive measurement to analyse the synergy relationship between water consumption of crop production and economic value creation. To eliminate the influence of inflation, we use the consumer price index (CPI) to calculate the inflation rate of China based on 2001 and to convert the annual crop current price into the 2001 constant Chinese Yuan price (Constant 2001 CNY). Then, we convert it to the 2001 constant American dollar price (Constant 2001 USD).

Referring to Chouchane et al. (2015), when calculating the blue and green EWF, we distinguish between irrigation and rainfed agricultural modes. In rainfed agriculture, the green EWF (EWF_{g,rf}) is obtained by dividing the green water consumption per unit yield under rainfed condition by the unit price of crops, as shown in Eq. (13). Compared to rainfed agriculture, the ratio of crop yield increment under full irrigation is obtained by AquaCrop model. We use it to distinguish the blue and green EWF in irrigation agriculture (EWF_{b,ir}, EWF_{g,ir}), as shown in Eqs. (14) - (16):

159
$$EWF_{g,rf} = \frac{CWU_{g,rf}}{Y_{RF} \times UP},$$
(13)

$$160 \quad \alpha = \frac{Y_{IR} - Y_{RF}}{Y_{IR}},\tag{14}$$

161
$$EWF_{b,ir} = \frac{CWU_{b,ir}}{Y_{IR} \times UP \times \alpha},$$
 (15)

162
$$EWF_{g,ir} = \frac{CWU_{g,ir}}{Y_{IR} \times UP \times (1-\alpha)},$$
 (16)

where $CWU_{g,rf}$ (m³ ha⁻¹) represents the consumption of green water per unit area in rainfed agriculture; $CWU_{b,ir}$ (m³ ha⁻¹) and CWU_{g,ir} (m³ ha⁻¹) represent the consumption per unit area in irrigation agriculture of blue and green water, respectively; α is the ratio of crop yield increment under full irrigation obtained by AquaCrop model; Y_{RF} (kg ha⁻¹) and Y_{IR} (kg ha⁻¹) represent the simulated crop yield after calibrated at provincial level under the rainfed and irrigation modes, respectively. The EWF_{g,rf} represents the amount of green water consumption per economic benefit unit in rainfed agriculture (also refers to the amount of green water input for each additional economic benefit unit); EWF_{b,ir} (EWF_{g,ir}) refers to the additional amount of blue (green) water for each additional unit economic benefit under the same green (blue) water input in irrigation agriculture.

170 **2.4 Spatial and temporal evolution of WFs**

The Mann-Kendall (M-K) trend test (Mann, 1945; Kendall, 1975) is used to test the annual variation trend of WF of crop production from 2001 to 2016. When using M-K test for trend analysis, the null hypothesis H₀ is the that all variables in WF time series $\{WF_i | i = 1, 2, ..., 16\}$ are independent and identical in distribution, with no variation trend; the alternative hypothesis H₁ is that all *i*, *j*≤16 and *i*≠*j*, in the distribution of *WF_i* and *WF_j* are different, with an obvious upward or downward trend in the sequence. The M-K statistic S is shown in Eq. (17):

176
$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(WF_j - WF_i),$$
(17)

where WF_j and WF_i are the data values of year j and i of the WF time series, respectively; n is the length of the data sample, 16; sgn is sign function, depicted in Eq. (18).

179
$$sgn(\theta) = \begin{cases} 1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases}$$
 (18)

180 When $n \ge 8$, the M-K statistic S roughly follows a normal distribution, whose mean value is zero, and the variance can be 181 calculated by Eq. (19).

182
$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{8} t_p(t_p-1)(2t_p+5)}{18},$$
 (19)

where g is the number of tied groups, and t_p is the number of data values in the Pth group (Kisi and Ay, 2014). When n >10, the test statistic Z_c converges to the standard normal distribution, which is calculated by Eq. (20).

185
$$Z_{c} = \begin{cases} (S-1)/\sqrt{Var(S)} & S > 0\\ 0 & S = 0\\ (S+1)/\sqrt{Var(S)} & S < 0 \end{cases}$$
(20)

Using two-tailed test, when the absolute value of Z_c exceeds 1.96 and 2.58, it means that the significance test of 95% and 99% has been passed, respectively. The positive Z_c indicates an upward trend, while a negative value means a downward trend.

The first law of geography states that everything is related, and things close to each other are more relevant (Tobler, 1970). The global and local spatial relevance of WF is expressed by the index Moran's I (Moran, 1950). A positive spatial autocorrelation exists, when the high or low values of the feature variables of adjacent regions show a clustering tendency in space; and a negative spatial autocorrelation means that the value of the feature variables of adjacent regions is opposite to that of the variable of the examined region. The Global Moran's I is used to evaluate the overall spatial relevance of WF of crop production, shown in Eq. (21).

194
$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (WF_i - \overline{WF}) (WF_j - \overline{WF})}{\sum_{i=1}^{n} (WF_i - \overline{WF})^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}},$$
(21)

where n is the number of provinces, 31; WF_i is crop WF of province i; \overline{WF} is the average WF; and W_{ij} is the spatial weight between the province i and j, which represents the potential interaction forces between the spatial units. When province i and j are adjacent, W_{ij}=1; when not adjacent, W_{ij}=0. At the given significance level (0.05 in this study), if the Global Moran's I is 198 significantly positive, it indicates that provinces with similar geographical attributes are clustered in space. On the contrary, if 199 the Global Moran's I is significantly negative, it means that provinces with different geographical attributes are clustered in 200 space. Local Moran index (LISA) (Anselin, 1995) is used to detect whether there is local clustering of attributes, and the level 201 (high or low) of the WF of a province is shown by the LISA cluster map. The LISA cluster map contains four types (Anselin, 202 2005): high-high (H-H) and low-low (L-L) indicate that the level (high or low) of WF in this province is consistent with adjacent provinces; high-low (H-L) and low-high (L-H) mean that the level (high or low) of WF in this province is 203 204 opposite to adjacent provinces. The analysis of spatial autocorrelation can be realised by the GeoDa. The GeoDa is a free 205 software program intended to serve as a user-friendly and graphical introduction to spatial analysis. It includes functionality 206 ranging from simple mapping to exploratory data analysis, the visualization of global and local spatial autocorrelation, and 207 spatial regression. A key feature of the GeoDa is an interactive environment that combines maps with statistical graphics, using 208 the technology of dynamically linked windows. In terms of the range of spatial statistical techniques included, the GeoDa is 209 most alike to the collection of functions developed in the open-source R environment (Anselin et al., 2006).

210 2.5 The synergy evaluation index (SI) of PWF and EWF

The synergy evaluation index (SI) in the current study is the measure of the synergy levels between the PWF and EWF of crops, by summing up their corresponding difference between the water footprint and the base value divided by the range (the maximum minus the minimum) of the water footprint. Here, we adopt the national average level water footprint value as the reference for comparison. The SI is calculated as follows:

215
$$SI_{i,j,c} = \frac{\overline{PWF_{j,c}} - PWF_{i,j,c}}{PWF_{j,c,max} - PWF_{j,c,min}} + \frac{\overline{EWF_{j,c}} - EWF_{i,j,c}}{EWF_{j,c,max} - EWF_{j,c,min}},$$
(22)

where $SI_{i,j,c}$ is the synergy evaluation index of PWF and EWF of crop c at province i in year j, $\overline{PWF_{j,c}}(m^3 kg^{-1})$ and $\overline{EWF_{j,c}}(m^3 kg^{-1})$ and $\overline{EWF_{j,c}}(m^3 kg^{-1})$ are the averages at the national level in year j. Obviously, the absolute value of the difference between the WF and their corresponding national average level cannot exceed the maximum minus minimum values. Therefore, the absolute value of SI cannot exceed 2. When the PWF and EWF in a region are both lower than the respective average at the national level, the SI of the region must be positive; when the PWF and EWF in a region are both higher than the respective average at the national level, the SI of the region must be negative. When one is higher, and the other is lower than the corresponding average, the SI may be positive or negative, depending on the difference between the provincial value and the national average.

223 2.6 Data sources

The planting area and yield data of each province were obtained from NBSC (2019). The provincial price data of crops were obtained from the China National Knowledge Infrastructure (CNKI, 2019). The current crop prices were converted to the constant prices using the inflation rate based on 2001. The consumer price index (CPI), which is used to calculate the inflation 227 rate, was retrieved from NBSC (2019). The exchange rate used to convert local constant prices into American constant prices 228 was taken from The World Bank (2019). The meteorological data on daily precipitation, daily mean maximum temperature 229 and daily mean minimum temperature required for the AquaCrop model of 698 meteorological stations in the study area (see 230 Fig.1) were downloaded from CMDC (2019). The irrigation and rainfed areas of crops were retrieved from MIRCA2000 231 (Portmann et al., 2010). The soil texture data were taken from the ISRIC database (Dijkshoorn et al., 2008). The soil water 232 content data were from Batjes (2012); The dates of planting of crops referred to (Chen et al., 1995). The harvest indexes were 233 taken from Xie et al. (2011) and Zhang and Zhu (1990). Crop growth periods and maximum root depths were taken from Allen 234 et al. (1998) and Hoekstra and Chapagain (2007).

235

236 Figure 1. Considered weather stations across mainland China.

237

238 3 Results

239 3.1 Temporal and spatial evolution of PWF

At the national average level, the PWF of both grain and cash crops showed a significant downward trend over the study period 2001-2016. With the increase of crop yield (grain crop increasing by 26%, cash crop increasing by 62%), the PWF of grain crop decreased by 20% from 1.16 m³ kg⁻¹ to 0.93 m³ kg⁻¹ (Fig. 2a); and the PWF of cash crop decreased by 35% from 0.70 m³ kg⁻¹ to 0.46 m³ kg⁻¹ (Fig. 2b). As for the composition of the WF, the proportion of blue WF of crop production showed a decreasing trend. The proportion of blue WF of grain and cash crops decreased from 39% and 17% in 2001 to 34% and 14% in 2016, respectively.

246

Figure 2. Interannual variability of national average production-based water footprint (PWF) of (a) grain and (b) cash crops in
China over 2001-2016.

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Table 2 lists the PWF, yield and blue and green water consumption by crops under irrigated and rainfed agriculture in 2001

- and 2016. Concerning grain crops, soybean had the highest PWF (2.79 $m^3 kg^{-1}$ in 2016), followed by spring wheat (1.51 m^3
- kg^{-1} in 2016). Rice had the lowest PWF (0.78 m³ kg⁻¹ in 2016). Among cash crops, cotton had the highest PWF (3.68 m³ kg⁻¹
- 253 in 2016), while sugar beet consumed the least water per yield (0.06m³ kg⁻¹ in 2016). The proportion of blue WF in spring

254 wheat was the highest (69% in 2016). Cotton had the highest proportion of blue WF (32% in 2016) in cash crops. Winter wheat 255 is the grain crop with the highest output in China, and its PWF decreased by 29% (from 1.47 m³ kg⁻¹ in 2001 to 1.04 m³ kg⁻¹ in 2016). Cotton is the cash crop with the highest water consumption per yield, and its PWF decreased by 31% (from 5.29 m³ 256 kg⁻¹ in 2001 to 3.68 m³ kg⁻¹ in 2016). The M-K test results of each crop's PWF in Table 3 further confirm the above views. The 257 PWF and yield of different crops had different temporal evolutions. The temporal trends in the PWF_b and PWF_g of a same 258 crop were also different. Among grain crops, winter wheat had the lowest M-K statistical value in PWF (-4.547) and the highest 259 in yield (5.178) jointly showing an obvious positive trend on improving water use efficiency. While the M-K statistic value of 260 261 soybean was only -0.675, which meant that the PWF of soybean had little decrease. Soybean planting was dominated by 262 individual farmer mode, with small and fragmented scales and a low planting mechanization degree. Moreover, the harvested 263 area was shrunk (7,202 thousand hectares in 2016, 24% less than 2001). For cash crops, the changes of PWF and yield were most pronounced for fruit crops (apple and citrus). The M-K test result of PWF_b of cotton with highest water consumption 264 intensity was zero, with almost no changes, given little changes in the yield level at most cotton growing areas. 265

266

Table 2. National average production-based water footprint (PWF) and economic value-based water footprint (EWF) of cropsin China for the years 2001 and 2016.

269

Table 3. M-K analysis of production-based water footprint (PWF) and economic value-based water footprint (EWF) of cropsin China.

272

273 Figure 3a and 3b show the spatial distribution of PWF of grain and cash crops across 31 provinces, respectively, in four 274 representative years (2001, 2006, 2011 and 2016). The PWF of grain crop was overall higher in northwest of China, represented 275 by provinces Shaanxi, Gansu and Ningxia, with the phenomenon of clustered distribution. The south-eastern coastal areas such 276 as Guangdong, Fujian and Zhejiang were at a relatively low level. The main reason behind is that the drier northwest, where 277 grows wheat and maize, has relatively higher evapotranspiration so that higher PWF. While the water-abundant and wet 278 southeast coastal provinces grow rice with a lower PWF. Consistently with the national level analysis, the PWF of the 31 279 provinces decreased significantly over time (Fig. 3a). Specifically, in north-western China, Gansu province, where the water-280 intensive wheat and maize were the main grain crops (wheat and maize accounting for 95% of grain crops in 2016), had the largest grain crop PWF (mean 1.43 m³ kg⁻¹) and showed an obvious downward trend, which decreased by 30% from 1.73 m³ 281 kg⁻¹ in 2001 to 1.21 m³ kg⁻¹ in 2016. Concerning the composition of blue and green water, Xinjiang had the largest proportion 282

- of blue water in grain crops among the 31 provinces, with annual average of 75%, far higher than the national average (36%);
- the proportion of blue water in grain production in Jilin province was the smallest, with annual average of 20%.

285 Differently from grain crop, the PWF of cash crop was higher in the Beijing-Tianjin-Hebei region, and lower in Inner Mongolia 286 province and the southern areas (Guangdong, Guangxi and Hainan), without an obvious clustered characteristic (Fig. 3b). This 287 can be interpreted that regarding the cash crops, the dominant crop differs among provinces which resulted in obvious scattered characteristics in related WFs. For instance, cotton and groundnut with PWF of 3.68 m³ kg⁻¹ and 1.49 m³ kg⁻¹ (in 2016) were 288 the leading cash crops in Beijing-Tianjin-Hebei region whereas rapeseed of lower PWF (1.04 m³ kg⁻¹ in 2016) was the main 289 290 cash crop in Inner Mongolia. Specifically, during the study period, the PWF of cash crop in Tianjin where cotton was the main cash crop was the largest (3.31 m³ kg⁻¹ in 2011, much higher than the national level of 0.51 m³ kg⁻¹ the same year), with the 291 annual average of 2.90 m³ kg⁻¹. The PWF of cash crop in Guangxi where citrus and sugarcane were dominant was the smallest, 292 293 with annual average of 0.14 m³ kg⁻¹, much lower than the national level of 0.54 m³ kg⁻¹. Concerning the composition of blue 294 and green water, the proportion of blue water was larger in northern and north-eastern China, and lower in southern and 295 southwestern China. Among them, the proportion of blue water of cash crop was the largest in Jilin province, with annual 296 average of 35%, while the proportion of blue water in Qinghai province was less than 1%, which was the lowest in China. 297 These results can be explained by the fact that Jilin's main cash crop was groundnut (88% in 2016), with high proportion of 298 blue water consumption, while Qinghai's 99% of cash crops was rainfed rapeseed.

299

300 Figure 3. Temporal and spatial evolution of production-based water footprint (PWF) of (a) grain and (b) cash crops in China.

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Table 4 shows Global Moran's I of PWF of grain and cash crops. The annual average global Moran's I of PWF of grain crop was 0.263, with a clustered spatial distribution in most provinces, and gradually moderated over time (Moran's I decreased from 0.559 in 2001 to 0.214 in 2016). The spatial pattern of PWF of cash crop did not show obvious agglomeration, and the average Moran's I was only 0.163.

- 306
- Table 4. Moran's I test for production-based water footprint (PWF) and economic value-based water footprint (EWF) of cropproduction.

The LISA cluster map shows that the H-H regions of PWF of grain crop gathered in Gansu, Ningxia, Shaanxi and Inner 310 311 Mongolia, and the L-L regions gathered in Guangdong, Zheijang, Fujian, and Jiangxi (Fig. 4a). At the beginning of the study 312 period, the PWF in 2001 showed an obvious positive spatial correlation, with 13 significant provinces (Gansu, Ningxia, 313 Shaanxi, Shanxi, Inner Mongolia, and Hebei in H-H regions; Guangdong, Zhejiang, Fujian, Jiangxi, Anhui, Jiangsu, and Hunan 314 in L-L regions). In time, the H-H regions in north western China gradually decreased, leaving only Ningxia in H-H regions, while L-L regions remained relatively stable. Overall, there were 7 significant regions in 2016, indicating that the spatial 315 agglomeration of PWF of grain crop decreased with time. This indicates that with the development of water-saving technology 316 317 and the improvement of agricultural water resource management level, the utilization efficiency of agricultural water resources 318 in the arid northwest region has been gradually improved, while the gap with the more developed and water-rich southern 319 provinces is narrowing. As for cash crop, no obvious agglomeration existed (Fig. 4b).

320

321 Figure 4. The LISA cluster maps of production-based water footprint (PWF) of (a) grain and (b) cash crops.

322

323 **3.2 Temporal and spatial evolution of EWF**

Similar to the evolution of PWF, the EWF of both grain and cash crops showed a significant declining trend at the national average level. With the increase of crop price (grain crop increasing by 40%, cash crop increasing by 70%), the EWF of grain crop decreased by 44%, from 9.01 m³ USD⁻¹ to 5.04 m³ USD⁻¹ (Fig. 5a); the EWF of cash crop decreased by 62%, from 5.39 m³ USD⁻¹ to 2.05 m³ USD⁻¹ (Fig. 5b).

328 In terms of grain crop, the EWF_{b.ir} fluctuated, reaching the highest value of 25.58 m³ USD⁻¹ in 2002 and falling to the lowest 329 of 12.26 m³ USD⁻¹ in 2010. In contrast, the EWF_{g,ir} and EWF_{g,rf} showed a significant and steady declining trend, decreasing from 5.32 m³ USD⁻¹ and 9.05 m³ USD⁻¹ in 2001 to 2.96 m³ USD⁻¹ and 4.94 m³ USD⁻¹ in 2016, respectively. Among the three 330 331 types of WF, the EWF_{g,ir} was the lowest (mean 3.11 m³ USD⁻¹), EWF_{b,ir} was the highest (mean 15.49 m³ USD⁻¹), and EWF_{g,rf} (mean 5.31 m³ USD⁻¹) was close to the average EWF (5.41 m³ USD⁻¹) in irrigation and rainfed production modes. This suggests 332 333 that more water was required per additional benefit unit under irrigation than under rainfed mode, whereas in the irrigated 334 agriculture, compared with blue water, increasing the input of green water may result in more economic benefits. Therefore, 335 utilisation efficiency of green water resource for grain crops should be improved.

336 Concerning cash crop, the EWF_{b,ir} decreased by 50% from 10.54 m³ USD⁻¹ to 5.22 m³ USD⁻¹. Compared to grain crop, the

- difference between the EWF_{g,ir} and EWF_{g,ir} was smaller, with average values of $1.90 \text{ m}^3 \text{ USD}^{-1}$ and $2.48 \text{ m}^3 \text{ USD}^{-1}$, respectively.
- 338 In addition, compared to grain crop, the EWF of cash crop was lower, which indicated that cash crop production could get

339 more economic benefits per water consumption unit. Besides, increasing the input of green water resource could obtain higher

- 340 economic benefits, and the rainfed production had greater economic potential.
- 341

Figure 5. Interannual variability of economic value-based water footprint (EWF) of (a) grain and (b) cash crops in China over
2001-2016.

344

Table 2 lists the EWF by crops in 2001 and 2016 at the national scale. Among grain crops, soybean, which consumed the most water per yield unit (2.79 m³ kg⁻¹ in 2016), also had the highest EWF; the second most water-intensive, spring wheat (1.51 m³ kg⁻¹ in 2016) had the second highest EWF (8.02 m³ USD⁻¹ in 2016); rice, with the lowest water consumption per yield unit (0.78 m³ kg⁻¹ in 2016) also had the lowest EWF (3.39 m³ USD⁻¹ in 2016). Regarding cash crops, cotton, with the highest water consumption per yield unit (3.68 m³ kg⁻¹ in 2016) was the crop with the highest EWF (3.00 m³ USD⁻¹ in 2016); groundnut's EWF ranked second (2.76 m³ USD⁻¹ in 2016); sugar beet had lowest water consumption per yield unit (0.06 m³ kg⁻¹ in 2016), with an EWF (1.60 m³ USD⁻¹ in 2016) much lower than the average EWF of cash crops (2.05 m³ USD⁻¹ in 2016).

Sugarcane had the lowest EWF_{b,ir} (1.29 m³ USD⁻¹ in 2016). The difference between EWF_{g,ir} and EWF_{g,ir} of spring wheat was 352 the largest, which were 3.11 m³ USD⁻¹ and 6.94 m³ USD⁻¹, respectively, in 2016. The difference between EWF_{e,ir} and EWF_{e,ir} 353 of tobacco was the smallest, which were 0.59 m³ USD⁻¹ and 0.83 m³ USD⁻¹, respectively, in 2016. Table 2 also lists the annual 354 355 blue and green CWU and yield under irrigated and rainfed conditions by crops in China for the years 2001 and 2016. It can be seen that for all the crops, CWU_{g,ir} was 21% (sugarcane) -55% (spring wheat) smaller than CWU_{g,if} in 2016. Therefore, it is 356 possible to result in EWFg,ir being much smaller than EWFg,f. During the study period, the EWFg,f of cash crops decreased 357 358 most significantly. As for the EWF_{bir} , the downward trend of cash crops was more significant, compared to that of grain crops. 359 The M-K test results in Table 3 further confirmed the above results, as the M-K statistical values of all crops' EWF passed the 360 significance level test of p < 0.05. M-K test results for the EWF of most crops were at the similar significance level as for the 361 corresponding PWF. It is mainly because the M-K test results of the prices of most crops were at the same significant level as the corresponding M-K test results of the yields. Due to the significantly increased price, the EWF M-K test result of soybean 362 363 was -2.116, which was higher than the test result of corresponding PWF (-0.675). Cotton is another crop worthy of attention. 364 M-K test result for EWF of cotton was -2.476, whose significance level was lower than that of PWF. This is mainly due to 365 fluctuations in the price of cotton. In addition, it can be seen that the changes of $EWF_{b,ir}$ of most crops were not as obvious as those of EWF_{g,ir} and EWF_{g,ir}. It indicates that there is more potential in optimizing the economic benefit of agricultural blue 366 367 water input.

Figure 6a and 6b show the spatial distribution of EWF of grain and cash crops, respectively. Generally, the EWF of grain crop 368 369 was higher in Inner Mongolia and north-western China (Shaanxi, Gansu, Ningxia and Xinjiang); Guangdong, Jiangxi, Fujian, 370 Zhejiang and other south-eastern coastal provinces were at a relatively low level. The northwest, with higher PWF, has lower 371 crop prices due to the relatively underdeveloped economies. In contrast, the economically advanced southeast coastal 372 provinces have both low crop water consumption and higher prices. And the EWF of the 31 provinces showed a significant declining trend over time, which was consistent with the characteristics of PWF of grain crop above (Fig. 3a). Specifically, 373 Gansu province with the highest PWF of grain crop in north-western China (mean 1.43 $m^3 kg^{-1}$) also had the highest EWF in 374 the top three (mean 8.34 m³ USD⁻¹), with a significant decline of 46% over time, from 13.28 m³ USD⁻¹ in 2001 to 7.12 m³ 375 376 USD⁻¹ in 2016. Another high value area in the northwest is Shaanxi, where winter wheat and spring maize were the main grain crops (44% and 47% of all grain crops, respectively in 2016). The EWF and PWF in Shaanxi (mean 8.15 m³ USD⁻¹ and 1.39 377 m³ kg⁻¹) were second only to those in Gansu. In contrast, the EWF and PWF (mean 4.49 m³ USD⁻¹ and 0.94 m³ kg⁻¹) in Fujian, 378 379 with rice as the main grain crop (86% of all grain crops in 2016) were far lower than the national average (mean 5.41 m³ USD⁻) 1 and 1.01 m³ kg⁻¹). 380

381 Concerning the composition of blue and green water for grain crop, the $EWF_{b,ir}$ in north-western China was lower, while the 382 $EWF_{g,ir}$ and $EWF_{g,rf}$ were higher. In contrast, the $EWF_{b,ir}$ in southern China was higher, while the $EWF_{g,ir}$ and $EWF_{g,rf}$ were lower. Specifically, in the northwest region, Ningxia had the highest EWF_{g,if} and EWF_{g,if} (mean 5.25 m³ USD⁻¹ and 8.35 383 384 m³ USD⁻¹, respectively), while the EWF_{b,ir} was only 7.28 m³ USD⁻¹, far lower than the national average (15.49 m³ USD⁻¹). Instead, the EWF_{g,ir} and EWF_{g,rf} in Yunnan were close to the national average level (3.59 m³ USD⁻¹ and 5.31 m³ USD⁻¹), and 385 EWF_{b,r} was the highest (52.05 m³ USD⁻¹). This is mainly because Yunnan is located in the southwest, where the climate is 386 387 humid and rainfall is abundant. The yields of maize and rice mainly planted are basically guaranteed under the condition of natural rainfall, with an extremely limited increase brought by irrigation. The EWF of cash crop had no obvious spatial 388 389 clustered phenomenon, decreasing significantly over time in 31 provinces, which was consistent with the spatial evolution 390 characteristics of the corresponding PWF previously discussed (Fig. 3b).

391

Figure 6. Temporal and spatial evolution of economic value-based water footprint (EWF) of (a) grain and (b) cash crops inChina.

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Table 4 shows the global Moran's I of EWF of grain and cash crops. The average Moran's I of EWF of grain crop (0.482) was higher than the PWF (0.263). Spatial agglomeration existed in most provinces, which was more stable over time. Differently from grain crop, the spatial pattern of EWF of cash crop did not show obvious agglomeration, with average Moran's I of 0.016.

The LISA cluster maps of EWF of grain and cash crops are shown in Fig. 7. The H-H regions of EWF for grain crop were 398 399 mainly concentrated in Ningxia, Gansu, Shaanxi, Shanxi, Inner Mongolia, and L-L regions were mainly concentrated in 400 Guangdong, Zhejiang, Fujian, Jiangxi. During the research period, the EWF of grain crop showed an obvious and stable 401 positive spatial correlation. Generally, the spatial agglomeration pattern of EWF of grain crop was stable. As for cash crop, 402 the LISA maps of four representative years shows great changes. Only in 2011, it shows a certain positive spatial correlation, 403 with 4 provinces (Hunan, Hubei, Chongqing and Guizhou) in H-H regions. Overall, the EWF of cash crop did not show obvious 404 spatial agglomeration. For a same crop, the spatial variations of its PWF are defined by climate and productivity. The price is 405 one of the main factors defining the EWF. While in related to the cluster maps shown in the current results for grain and cash 406 crops, the main factor is the cultivation distribution. Regarding the grain crops, the cultivation distributions of major grain 407 crops in China show obvious spatial agglomeration characteristics. For instance, rice is mainly distributed in central and 408 southern China (Hubei, Hunan, Jiangxi, Guangdong and Guangxi). Winter wheat is concentrated in Huang-Huai-Hai Plain 409 (Shandong, Henan, Jiangsu, Anhui and Hebei). Whereas regarding the cash crops, the dominant crop differs among provinces 410 (see Fig. 10b) which resulted in obvious scattered characteristics in related WFs. For example, in the northwest regions, there is only Xinjiang where cotton is planted on a large scale, and almost no cotton is planted in the surrounding provinces. In 411 412 addition, crop prices in the main producing provinces are generally lower, while vary affected by the regional economic level. For example, both Henan and Shandong are the main producing areas of winter wheat, but the price (0.21 USD kg⁻¹ in 2016) 413 in Shandong, which has a more developed economy, was higher than that in Henan $(0.17 \text{ USD kg}^{-1})$. 414

415

416 Figure 7. The LISA cluster maps of economic value-based water footprint (EWF) of (a) grain and (b) cash crops.

417

418 **3.3** Synergy evaluation of PWF and EWF

419 Figure 8a and 8b show the SI between PWF and EWF of grain and cash crops across 31 provinces, respectively over years. 420 Concerning grain crop, the number of provinces with negative SI were increasing. Over time, the areas with negative SI 421 gradually expanded to the south. The SI was mostly negative in Beijing-Tianjin-Hebei, Inner Mongolia and north-western 422 China. In 2016, the SI of Shaanxi was -1.13, the lowest in China. The SI of Jiangxi, Chongqing, Hubei, Hunan, Jiangsu, 423 Zhejiang, Shanghai, and other coastal areas in south-eastern China was positive. In 2016, the SI of Jiangxi was 0.62, the highest 424 in China. Overall, the SI of grain crop was negative in Inner Mongolia and north-western China (Shaanxi, Gansu, Ningxia), 425 whereas in Guangdong, Jiangxi, Fujian, Zhejiang and other coastal areas in south-eastern China it was positive, with a clustered 426 distribution. With the development of water-saving technologies and the improvement of agricultural management, China has 427 made gratifying progress in the efficient use of water for crop production from a single physical or economic perspective. 428 However, only by combining the physical and economic perspectives can we gain a deeper understanding of the underlying

429 problems and catch the synergies, trade-offs and even lose-lose relationships between reducing the water resources input for

430 harvesting crop yields and optimizing the economic benefits per unit of water consumption in different regions.

431 As for cash crop, the SI of Tianjin, Jiangxi and Hunan was always negative, and the lowest in China (multi-year mean values 432 -0.98, -0.90 and -0.74, respectively). Overall, there were more provinces with negative SI of cash crop, and the incongruity 433 between PWF and EWF of cash crop was more significant than that of grain crop. Interestingly, the provinces with the most 434 severe negative SI for grain crops had positive SI for cash crops. The highest SI of cash crop in 2016 occurred in Shanghai 435 (0.39), which was lower than the SI of grain crop in the same year (0.45). At the same time, the SI of grain and cash crops in 436 Tianjin, Tibet and Xinjiang decreased significantly. In more provinces, the SI of grain and cash crop varied greatly and was 437 not synchronised. For example, the SI of grain crop in Inner Mongolia and Fujian increased significantly, while the SI of cash 438 crop showed a downward trend. Furthermore, the SI of cash crop in Shaanxi and Gansu increased significantly, while the SI 439 of grain crop did not change significantly.

440

441 Figure 8. Temporal and spatial evolution of synergy evaluation index (SI) of (a) grain and (b) cash crops.

442

443 Taking 2016 as an example, we further look at the reasons for the "lose-lose" relationship between reducing the water resources 444 input for harvesting crop yields and optimizing the economic benefits per unit of water consumption in both grain and cash 445 crops (see Fig. 9), from the perspective of planting structure (see Fig. 10). Shaanxi province had the highest PWF in China (1.23 m³ kg⁻¹), and the second highest EWF (7.48 m³ USD⁻¹). In Shaanxi, winter wheat and spring maize with high water 446 consumption and low yield accounted for more than 90% of the total sown area of grain crops, with yields lower than the 447 national averages by 24% and 26%, respectively. Moreover, the price of wheat in Shaanxi province (0.17 USD kg⁻¹) was lower 448 449 than the national average (0.19 USD kg⁻¹). The reasons for high water consumption per unit of grain production coupled with 450 poor economic benefits in Shaanxi province can be attributed to the above two points. In contrast, in Jiangxi province, where rice, which has low water consumption intensity, is the main grain crop (rice accounting for 95% of the grain crops), PWF and 451 EWF were 0.77 m³ kg⁻¹ and 3.63 m³ USD⁻¹, well below the national averages (0.93 m³ kg⁻¹, 5.04 m³ USD⁻¹). 452

As for cash crop, the PWF of Tianjin was $1.92 \text{ m}^3 \text{ kg}^{-1}$, the highest in China, and the EWF was $3.26 \text{ m}^3 \text{ USD}^{-1}$, the fifth highest in China, which was significantly higher than the national average ($2.05 \text{ m}^3 \text{ USD}^{-1}$). It can be seen from Fig. 10b that cotton accounted for the largest proportion (70%) in the planting structure of cash crops in Tianjin. Cotton consumed the most water per yield unit of cash crops, while the price unit of cotton in Tianjin was the second lowest in China (1.11 USD kg^{-1}), which did not reflect the advantage of cotton as a high-value crop. Jiangxi province showed the highest EWF in China ($3.86 \text{ m}^3 \text{ USD}^{-1}$) in the national average ($0.46 \text{ m}^3 \text{ kg}^{-1}$). Figure 10b shows that citrus (planting area accounting for 29% of cash crops) and rapeseed (planting area accounting for 48% of cash crops) are the main cash crops in Jiangxi. However, the price unit of citrus in Jiangxi was the third lowest (0.17 USD kg⁻¹, only 62% of the national average), and the yield of rapeseed was also the third lowest (1.34 t ha⁻¹, 32% lower than the national average). In contrast, the main cash crop in Shanxi was apple (planting area accounting for 87% of cash crops), with low water consumption intensity and a yield which was the second highest in China (28.5 t ha⁻¹), 1.5 times larger than the national average (18.9 t ha⁻¹).

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Figure 9. Production-based water footprint (PWF) versus economic value-based water footprint (EWF) of (a) grain and (b) cash crops per province in 2016.

467

468 Figure 10. Planting structure of (a) grain and (b) cash crops in 31 provinces in 2016.

469

470 4 Discussion

The goal of WF regulation is to reduce its magnitude to a sustainable level (Hoekstra, 2013), but the challenges faced during implementing sustainable development are rarely encountered in a single dimension. However, previous research has most commonly adopted a single perspective approach to WF analysis. Based on the temporal and spatial evolution of PWF and EWF, the synergy evaluation index (SI) is constructed to achieve a more comprehensive assessment in this study. This approach has led to some differences in the results of WF compared to previous research.

476 Table 5 compares the PWF results of crops production between the current study and previous ones. Differently from 477 Mekonnen and Hoekstra (2011) and Zhuo et al. (2016b), this study distinguishes between wheat and maize varieties when 478 calculating the WF, despite China's wheat production is mainly of winter wheat (accounting for 95% in 2016). Due to the 479 differences of varieties, water consumption intensity and planting conditions, it is necessary to distinguish between crops in 480 the provinces where spring wheat is the main crop. In addition, due to the differences in model selection and parameters, the 481 calculation results will also be different. For example, Mekonnen and Hoekstra (2011) used CROPWAT model and checked 482 the crop yield at the national scale, while this study chooses AquaCrop model and checks the crop yield at the provincial level. 483 Both the studies of Mekonnen and Hoekstra (2011) and Zhuo et al. (2016b) were based on the 5 arc-minute grid, while this 484 research calculates the WF based on the meteorological station scale. In general, however, the crop production WF in this 485 study is close to that of previous studies, which shows the rationality of the calculated results.

Table 6 compares the EWF of this study with previously calculated results of the economic water productivity. There were no existing EWF values for China's cases. We wish to show the available values on EWF of crops, while for countries other than China. Since the economic water productivity is numerically equal to the reciprocal of the EWF, the previous results are expressed in the form of EWF for comparison. The results for wheat production show that, although the average EWF is close, differences in crop varieties, planting environment, and climate condition result in huge differences in EWF_{b,ir} under the same production mode. Therefore, specific problems should be investigated separately. Selection and adjustment of production mode should be made according to local conditions to promote coordinated development.

From the results of the multi-perspective analysis conducted in this study, we found that with the increase of yield and price, the PWF and EWF of crop production both showed a decreasing trend, and the EWF decreased more significantly compared with the PWF. The change of WF of cash crops was more obvious than that of grain crops. In terms of the spatial pattern, compared with cash crops, WF of grain crops had a more significant spatial correlation, and the spatial distribution of PWF was similar to that of EWF. H-H areas mainly gathered in north-western China, while L-L areas in south-eastern coastal provinces. The average Moran's I of EWF (0.482) was higher than that of PWF (0.263).

499 Moreover, results show that as for grain production at the national level, the EWF_{h,ir} (mean 15.49 m³ USD⁻¹) was much higher than the EWF_{g,ir} (mean 3.11 m³ USD⁻¹), and the EWF_{g,ff} (mean 5.31 m³ USD⁻¹) was the closest to the average EWF in irrigation 500 501 and rainfed agriculture (mean 5.41 m³ USD⁻¹). Compared with grain crops, the difference between EWF_{g,if} and EWF_{g,if} of cash 502 crops was smaller, with average values of 1.90 m³ USD⁻¹ and 2.48 m³ USD⁻¹, respectively. Moreover, the EWF of cash crops 503 was lower than that of grain crops. It was more cost-effective to increase the input of green water than that of blue water during 504 crop production. In north-western China, the EWF_{b,ir} was lower, while the EWF_{g,ir} and EWF_{g,rf} were higher; on the contrary, in 505 southern China, the EWF_{b,ir} was higher, while the EWF_{g,ir} and EWF_{g,ir} were lower. Therefore, the utilisation efficiency of green 506 water resources should be improved through water retention by tillage system and mulching. Meanwhile, more blue water can 507 be generated through rainwater harvesting (Hoekstra, 2019). Specifically, we suggest two measures to increase the blue water 508 efficiency in northern China. One is the rainwater harvesting in rainy season, especially for the short-time heavy rain which 509 cannot effectively used by crops but easily cause soil erosion. The other one is reducing blue water consumption and loss at 510 field by popularizing water-saving irrigation techniques and mulching practices. Such measure is helpful to improve the 511 utilisation efficiency of both blue and green water. Based on the current results, we recommend the government to improve 512 agricultural water use efficiency through the extension of water-saving irrigation techniques and better agricultural inputs 513 management, especially in northwest China. High water consumption and low economic value crops' acreages in non-primary 514 production areas should be reduced. For the southern regions with abundant rainwater resources, the economic benefits of 515 irrigation are very limited, on the contrary, rainfed agriculture has obvious advantages and the potential to increase economic 516 benefits. Therefore, farmers should improve the water conservation rate and the utilization efficiency of green water through 517 farming system and coverage to reduce the amount of water used for irrigation. The government should also give financial

518 subsidies for agricultural production to those provinces where there were lose-lose relationships between reducing the water 519 resources input for harvesting crop yields and optimizing the economic benefits per unit of water consumption. Finally, 520 improve the field managements especially in utilization rate of chemical fertilizers and pesticides to increase agricultural 521 productivity further (Zhang et al., 2013).

There was a serious lose-lose relationship between reducing the water resources input for harvesting crop yields and optimizing the economic benefits per unit of water consumption both in grain and cash crops. In terms of grain production, the water consumption per yield was large, but the economic benefit per water consumption unit was poor in the northwest region, while the opposite was true in the southeast coastal region. Over time, the lose-lose relationship has not been alleviated, showing a relatively stable spatial pattern. Through analysis, this study shows that the unreasonable regional planting structure and crop price may be the direct cause of the incongruity between water resource consumption and economic value creation for crop production in China.

529 The study reveals the synergies and trade-offs of crop PWFs and EWFs. However, it is undeniable that there are some 530 limitations and shortcomings. Firstly, in the calculation of WF, although the accuracy of AquaCrop model in simulating crop 531 water consumption and yield, soil field water, and fertiliser management types under different climatic conditions has been 532 widely demonstrated, the uncertainty of results caused by the uncertainty of input parameters must be acknowledged (Zhuo et 533 al., 2014). Secondly, this paper does not make a specific distinction between crop irrigation methods. In fact, the difference of 534 WF results caused by different irrigation methods cannot be ignored (Wang et al., 2019). Thirdly, when calculating the WF, it 535 is assumed that the change of crop irrigation and rainfed planting area only occurs in the data grid based on 2000, and the 536 migration of crop harvesting zone is not considered. Finally, this study does not focus specifically on the effects of field water 537 and fertiliser management measures. Although there are restrictions on the availability of crop price unit data in the selection 538 of research objects, it is still representative because the crops selected in this paper accounts for more than 85% of the national 539 crop production. As for the study perspective, this article focuses on trade-offs between water consumption and economic 540 value creation in crop production. In fact, the ecological impacts on the environment cannot be ignored. Therefore, further 541 research is expected to tackle this limitation by including the ecological impacts on the environment in a more comprehensive 542 assessment. In addition, it should be noted that in the current study, the SI measures, considering the spatial heterogeneities in 543 crop WFs among provinces, the synergy levels between the current PWF and EWF. The synergy (both the PWF and EWF are 544 lower than the national averages), trade-off (one is higher than the national average while the other is lower), or lose-lose (both 545 are higher than the national averages) situation can be identified. The most optimized situation means high economic value 546 generated by low water consumption. For the two provinces with high SI values, they were both in an advantageous position, 547 while the one with a higher SI values performed better in terms of synergy between PWF and EWF. If the reference value is 548 set by the WF benchmark (Mekonnen and Hoekstra, 2014b), then the SI will show information on efficiency. The meaning is 549 totally different from the current one. Choosing proper reference value for different functions is highly recommended.

Table 5. Comparison between production-based water footprint (PWF) of crops production in mainland China in the current study and previous studies.

553

- Table 6. Comparison between economic value-based water footprint (EWF) in the current results and previous studies.
- 555

556 5 Conclusions

557 Based on temporal and spatial evolution analysis of WF of China's crop production from a physical and economical perspective,

this study makes a comprehensive assessment by constructing a SI between PWF and EWF, and reveals the synergies and trade-offs of crop water productivity and its economic value. Results show that:

560 (1) With the increase of yield unit and price unit, the PWF and EWF of crop production both showed a decreasing trend, and 561 the EWF decreased more significantly. The change of WF of cash crops was more obvious than that of grain crops.

562 (2) Compared to cash crops, WF of grain crops had a more significant spatial correlation, and the spatial distribution of PWF

was similar to that of EWF. H-H areas mainly gathered in north-western China, while L-L areas in southeast coastal provinces.
The average Moran's I of EWF (0.482) was higher than that of PWF (0.263).

(3) The economic benefits of blue water and green water differed greatly, and the difference showed to be more significant for grain crop than for cash crop. Moreover, the EWF of cash crops was lower than that of grain crops. It was found to be more cost-effective to increase the input of green water than that of blue water during crop production.

(4) In terms of grain production, the water consumption per yield unit was large but the economic benefit per water consumption unit was poor in the northwest region, while the opposite was true in the southeast coastal region. The trade-offs have not been alleviated over time, showing a relatively stable spatial pattern. These findings show that the unreasonable regional planting structure and crop price may be the direct cause of the lose-lose relationships between water resource consumption and economic value creation for crop production, so this issue should be tackled by coordinated governmental action, to balance the economic benefits of the water-intensive crops in different regions.

574 Data availability

575 Data sources of carrying out the study are listed in the section 2.6 Data sources. Data generated in this paper is available by 576 contacting L Zhuo.

577 Author contributions

La Zhuo and Xi Yang designed the study. Xi Yang carried it out. Xi Yang prepared the manuscript with contributions from allco-authors.

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738 Figure 1: Considered weather stations across mainland China.



Figure 2: Interannual variability of national average production-based water footprint (PWF) of (a) grain and (b) cash crops in

742 China over 2001-2016.



Figure 3: Temporal and spatial evolution of production-based water footprint (PWF) of (a) grain and (b) cash crops in China.



Figure 4: The LISA cluster maps of production-based water footprint (PWF) of (a) grain and (b) cash crops.



Figure 5: Interannual variability of economic value-based water footprint (EWF) of (a) grain and (b) cash crops in China over 2001 2016.





751 Figure 6: Temporal and spatial evolution of economic value-based water footprint (EWF) of (a) grain and (b) cash crops in China.



753 Figure 7: The LISA cluster maps of economic value-based water footprint (EWF) of (a) grain and (b) cash crops.



Figure 8: Temporal and spatial evolution of synergy evaluation index (SI) of (a) grain and (b) cash crops.

Figure 9: Production-based water footprint (PWF) versus economic value-based water footprint (EWF) of (a) grain and (b) cash crops per province in 2016.

760 Figure 10: Planting structure of (a) grain and (b) cash crops in 31 provinces in 2016.

762 Table 1. Number of meteorological stations per province.

Region	Province	Number of weather stations	Climatic zone		
North central	Beijing	3	Temperate		
North-central	Tianjin	3	Temperate		
	Shanxi	27			
	Inner Mongolia	36	Continental temperate &		
Northeast	Liaoning	25	temperate		
	Jilin	29	temperate		
	Heilongjiang	34			
	Hebei	19			
Huang-Huai-Hai	Shandong	21	Temperate		
	Henan	17			
	Anhui	21			
Southeast	Shanghai	1	Sub tropics		
Southeast	Zhejiang	21	Sub-uopies		
	Fujian	22			
Vangtze (middle & lower	Jiangsu	22			
reaches)	Jiangxi	26	Sub-tropics		
Teaches)	Hubei	27			
	Hunan	29			
South-central	Guangdong	36	Sub-tropics & tropics		
Bouil central	Guangxi	18	Sub hopies & hopies		
	Hainan	5			
	Chongqing	11			
Southwest	Sichuan	38	Sub-tropics		
Bouinwest	Guizhou	31	bub uopies		
	Yunnan	25			
	Tibet	17			
	Shaanxi	32			
Northwest	Gansu	23	Continental temperate &		
1 tortil west	Qinghai	25	plateau and mountain		
	Ningxia	12			
	Xinjiang	42			

Table 2. National average production-based water footprint (PWF) and economic value-based water footprint (EWF) of crops in China for the years

Table 2. Nation

 766
 2001 and 2016.

		Irrigated						Rainfed				Price	Yield	PWF _b	PWFg	PWF	EWF
		CWU _{b,ir}	CWU _{g,ir}	PWFir	EWF _{b,ir}	EWF _{g,ir}	Y _{IR}	CWU _{g,rf}	PWFrf	EWF _{g,rf}	YRF	•			0		
Crop	Year	m ³ ha ⁻¹	m ³ ha ⁻¹	m ³ kg ⁻¹	m ³ USD ⁻¹	m ³ USD ⁻¹	kg ha ⁻¹	m ³ ha ⁻¹	m ³ kg ⁻¹	m ³ USD ⁻¹	kg ha ⁻¹	USD kg ⁻¹	kg ha ⁻¹	m ³ kg ⁻¹	m ³ kg ⁻¹	m ³ kg ⁻¹	m ³ USD ⁻¹
Grain	2001	3266	2599	1.16	19.93	5.32	5059	4420	1.17	9.05	3788	0.13	4596	0.45	0.71	1.16	9.01
crop	2016	2995	2797	0.94	15.70	2.96	6193	4674	0.91	4.94	5153	0.18	5780	0.32	0.61	0.93	5.04
Winter	2001	3590	2617	1.47	22.95	6.91	4220	4428	1.48	11.68	2987	0.13	3806	0.62	0.85	1.47	11.62
wheat	2016	3329	2776	1.05	15.02	3.19	5819	4726	1.02	5.42	4639	0.19	5402	0.40	0.64	1.04	5.54
Spring	2001																
wheat	2016	4900	1750	1.52	18.88	3.11	4373	3898	1.30	6.94	2992	0.19	4237	1.05	0.46	1.51	8.02
Spring	2001	4683	2279	1.19	18.57	5.27	5860	4268	1.15	9.87	3701	0.12	4666	0.45	0.72	1.17	10.04
maize	2016	3943	2557	0.86	16.96	3.41	7586	4633	0.80	6.18	5791	0.13	6435	0.22	0.60	0.82	6.36
Summer	2001	2822	2844	1.13	36.18	5.58	5030	4681	1.07	9.19	4362	0.12	4725	0.32	0.78	1.10	9.45
maize	2016	2564	2983	0.99	64.25	4.35	5605	4773	0.90	6.96	5297	0.13	5439	0.21	0.73	0.94	7.28
Rice	2001	2868	2568	0.86	23.78	3.71	6312	4324	0.80	6.25	5375	0.13	6163	0.39	0.46	0.85	6.63
	2016	2583	2876	0.79	20.79	1.96	6940	4563	0.71	3.11	6398	0.23	6862	0.33	0.45	0.78	3.39
Soybean	2001	3511	2677	2.84	19.31	8.15	2183	4378	3.12	13.32	1405	0.23	1625	0.61	2.40	3.01	12.87
	2016	2928	2779	2.80	24.43	5.21	2040	4627	2.78	8.68	1666	0.32	1796	0.57	2.22	2.79	8.70
Cash	2001	4224	3106	0.81	10.54	4.01	9033	3955	0.66	5.11	5954	0.13	6512	0.12	0.58	0.70	5.39
сгор	2016	3722	3469	0.55	5.22	1.57	13158	4268	0.43	1.94	9945	0.22	10526	0.07	0.39	0.46	2.05
Ground-	2001	3810	2614	2.07	41.27	3.40	3103	4399	1.59	5.72	2771	0.28	2888	0.46	1.31	1.77	6.37
nut	2016	3228	3075	1.70	69.28	1.57	3712	4997	1.38	2.55	3626	0.54	3657	0.31	1.18	1.49	2.76
Rapeseed	2001							2066	1.29	5.92	1597	0.22	1597		1.29	1.29	5.92
	2016							2065	1.04	2.73	1984	0.38	1984		1.04	1.04	2.73
Cotton	2001	5291	2868	6.21	20.35	3.05	1314	4987	4.85	5.30	1029	0.92	1107	1.31	3.98	5.29	5.78
	2016	5035	3093	4.69	17.62	1.68	1732	4501	3.00	2.45	1500	1.23	1584	1.16	2.52	3.68	3.00
Sugarcane	2001	4199	5367	0.09	3.47	4.35	106621	7357	0.14	5.97	53811	0.02	60625	0.01	0.12	0.13	5.50
	2016	3809	5805	0.07	1.29	2.04	139879	7315	0.11	2.58	68656	0.04	74550	0.01	0.09	0.10	2.43
Sugar beet	2001							3850	0.14	5.43	26764	0.03	26764		0.14	0.14	5.43
	2016	100.6	2225	0.55	24.04	2.02	10504	3602	0.06	1.60	57547	0.04	57547	0.05	0.06	0.06	1.60
Apple	2001	4826	3235	0.75	34.96	2.83	10704	5114	0.54	4.47	9551	0.12	9687	0.05	0.51	0.56	4.71
	2016	4186	3579	0.36	4.96	0.74	21677	5457	0.30	1.13	18454	0.26	18883	0.03	0.28	0.31	1.17
Citrus	2001	3535	5017	0.94	45.86	3.68	9077	7534	0.88	5.52	8591	0.16	8769	0.15	0.75	0.90	5.68
	2016	3004	5318	0.53	9.43	1.34	15613	2570	0.55	2.00	14451	0.27	14701	0.04	0.50	0.54	1.99
Tobacco	2001	2365	2564	2.57	12.92	1.66	1918	3579	2.09	2.32	1715	0.90	1754	0.26	1.93	2.19	2.43
	2016	2010	2741	2.08	4.69	0.59	2289	3832	1.83	0.83	2094	2.21	2141	0.22	1.67	1.89	0.86

		Price	Yield	PWFb	PWFg	PWF	EWF	EWF _{b,ir}	EWF _{g,ir}	EWF _{g,rf}
		USD kg ⁻¹	kg ha ⁻¹	m ³ kg ⁻¹	m ³ kg ⁻¹	m ³ kg ⁻¹	m ³ USD ⁻¹			
Grain	Zc	3.557	5.088	-4.727	-4.277	-4.997	-4.097	-3.017	-4.187	-4.007
crop	Signific	**	**	**	**	**	**	**	**	**
Winter	Zc	4.007	5.178	-3.737	-4.547	-4.547	-4.547	-1.936	-4.547	-4.547
wheat	Signific	**	**	**	**	**	**		**	**
Spring	Zc	4.007	4.457	-0.135	-3.107	-2.476	-2.746	0.045	-2.926	-2.746
wheat	Signific	**	**		**	*	**		**	**
Spring	Zc	3.107	3.647	-4.097	-2.476	-4.097	-3.647	-2.386	-3.377	-3.647
maize	Signific	**	**	**	*	**	**	*	**	**
Summer	Zc	3.107	4.277	-3.647	-3.197	-3.287	-3.377	0.495	-3.647	-3.467
maize	Signific	**	**	**	**	**	**		**	**
	Zc	3.647	4.637	-3.107	-3.017	-3.377	-4.367	-0.315	-3.827	-4.277
Rice	Signific	**	**	**	**	**	**		**	**
	Zc	2.116	1.126	1.846	-1.396	-0.675	-2.116	0.135	-2.656	-2.296
Soybean	Signific	*					*		**	*
Cash	Zc	3.287	4.547	-4.007	-4.547	-4.637	-3.737	-3.017	-3.647	-3.737
crop	Signific	**	**	**	**	**	**	**	**	**
Ground-	Zc	2.926	4.547	-3.467	-3.287	-3.917	-3.377	0.405	-3.017	-3.197
nut	Signific	**	**	**	**	**	**		**	**
	Zc	3.197	4.097	2.386	-2.476	-2.476	-3.377			-3.377
Rapeseed	Signific	**	**	*	*	*	**			**
	Zc	0.135	4.277	0	-4.187	-4.007	-2.476	0.045	-2.656	-2.926
Cotton	Signific		**		**	**	*		**	**
	Zc	3.017	3.467	-3.377	-2.116	-2.476	-3.557	-3.737	-3.647	-3.557
Sugarcane	Signific	**	**	**	*	*	**	**	**	**
Sugar	Zc	3.647	4.727	-0.045	-4.457	-4.457	-4.457			-4.457
beet	Signific	**	**		**	**	**			**
	Zc	3.197	5.358	-4.907	-5.088	-4.997	-3.557	-2.926	-3.557	-3.557
Apple	Signific	**	**	**	**	**	**	**	**	**
	Zc	1.576	5.178	-4.997	-4.817	-4.997	-3.737	-3.107	-3.647	-3.647
Citrus	Signific		**	**	**	**	**	**	**	**
	Zc	4.817	2.926	-0.855	-2.836	-2.746	-4.817	-3.917	-4.997	-4.817
Tobacco	Signific	**	**		**	**	**	**	**	**

*** Significant at p < 0.05, ** significant at p < 0.01**

			Moran's I	Z-score	<i>p</i> -value
		2001	0.559	5.141	0.001
		2006	0.227	2.207	0.014
	Grain crop	2011	0.126	1.491	0.077
		2016	0.214	2.085	0.021
PWF		2001-2016	0.263	2.659	0.009
$(m^3 kg^{-1})$		2001	0.302	2.972	0.004
		2006	0.152	1.665	0.052
	Cash crop	2011	0.094	1.252	0.106
		2016	0.11	1.224	0.11
		2001-2016	0.163	1.756	0.05
		2001	0.585	5.392	0.001
		2006	0.395	3.887	0.001
	Grain crop	2011	0.311	3.073	0.003
		2016	0.618	5.393	0.001
EWF		2001-2016	0.482	4.518	0.001
(m ³ USD ⁻¹)		2001	-0.009	0.184	0.411
		2006	0.04	0.653	0.24
	Cash crop	2011	0.139	1.501	0.066
		2016	-0.145	-0.914	0.187
		2001-2016	0.016	0.418	0.307

771	Table 4. Moran's I test for production-based water footprint (PWF) and economic value-based water footprint (EWF) of crop
772	production.

776 Table 5. Comparison between production-based water footprint (PWF) of crops production in mainland China in the current study and previous

studies.

	PWF _b (m ³ kg ⁻¹)			PWFg(m ³ kg	g ⁻¹)		PWF(m ³ kg ⁻¹)		
	Current	Mekonnen	Zhuo et al.	Current	Mekonnen	Zhuo et al.	Current	Mekonnen	Zhuo et al.
	2001-2016	1996-2005	2008	2001-2016	1996-2005	2008	2001-2016	1996-2005	2008
Winter wheat	0.49	0.47	0.31	0.73	0.82	0.84	1.22	1.29	1.15
Spring wheat	1.03			0.56			1.59		
Spring maize	0.27	0.07	0.07	0.65	0.79	0.75	0.92	0.86	0.82
Summer maize	0.25			0.73			0.98		
Rice	0.36	0.25	0.38	0.46	0.55	0.96	0.82	0.80	1.34
Soybean	0.53	0.25	0.11	2.34	2.55	2.02	2.87	2.80	2.13
Groundnut	0.38	0.09	0.19	1.21	1.38	1.35	1.59	1.47	1.54
Rapeseed	0.00	0.00	0.00	1.18	1.39	1.74	1.18	1.39	1.74
Cotton	1.06	0.56		3.58	3.26		4.64	3.82	
Sugarcane	0.01	0.01	0.00	0.10	0.17	0.12	0.11	0.18	0.12
Sugar beet	0.00	0.00	0.00	0.10	0.15	0.07	0.10	0.15	0.07
Apple	0.04	0.03	0.04	0.35	0.80	0.31	0.39	0.83	0.35
Citrus	0.09	0.02		0.63	0.45		0.72	0.47	
Tobacco	0.23	0.25	0.01	1.67	2.01	1.63	1.90	2.26	1.64

Table 6. Comparison between economic value-based water footprint (EWF) in the current results and previous studies.

Reference	Case	Year/Period	EWF _{b,ir}	EWF _{g,ir}	EWF _{g,rf}	EWF
			m ³ USD ⁻¹			
Schyns and Hoekstra (2014)	Wheat in Morocco	1996-2005				12.50
Chouchane et al. (2015)	Wheat in Tunisia	1996-2005	8.33	11.11	10.00	10.00
Current study	Winter wheat in China	2001-2016	17.57	3.82	6.63	6.81
	Spring wheat in China		18.93	3.86	7.87	8.81