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

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Abstract

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

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 occupation and pollution of water in the process of production or consumption and assesses fresh water appropriation in its entirety (Hoekstra et al., 2011). As comprehensive index to evaluate types, quantities, and efficiency of water use in the process of crop production, the WF of crop production can be expressed based on both production (PWF, m^3 kg^{-1}) and economic value (EWF, m^3 per monetary unit) (Garrido et al., 2010;Hoekstra et al., 2011), which unifies the measurement of the physical and economic levels.

Garrido et al. (2010) firstly evaluated WF in terms of m^3 €$^{-1}$, from a perspective of hydrology and economy for agricultural production of Spain. They found that in areas where blue water was scarce but dominant in crop production, the scarce blue water resource was used to irrigate high-value crops, thus achieving higher yields and economic benefits, with a more efficient blue water utilisation with increasing scarcity. In a case study for Kenya, Mekonnen and Hoekstra (2014) encouraged to use domestic water resource for production of the rain-fed 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 were mainly used to produce export crops with relatively low economic value (in terms of USD m^{-3} and USD ha^{-1}), and that water-scarce countries should attribute great importance to the allocation of freshwater and adjust crop planting structure from the perspective of economic efficiency. Chouchane et al. (2015) quantified the WF in Tunisia and evaluated the blue and green economic water productivity and economic land productivity in irrigation and rainfed agriculture from an economic perspective. They showed that irrigation water was not generally used to increase economic water productivity (USD m^{-3}) but rather to increase economic land productivity (USD ha^{-1}), so it would be advantageous to expand the irrigated area of crops with high economic water productivity. Furthermore, in recent years, there have been studies on the dairy industry (Owusu-Sekyere et al., 2017a;Owusu-Sekyere et al., 2017b)， the meat industry (Ibidhi and Salem, 2018) and the wine industry (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 thus ignored the synergies and trade-offs between water consumption and economic value creation during crop production in WF assessment, which is undoubtedly of great significance.

Scientifically planning agricultural water resource utilisation and balancing crop production, water consumption and social economic development are severe challenges faced by all humankind. However, China, with millions of small farmers led by smallholder production, has become one of the regions facing the biggest challenges. (Tilman et al., 2011;Gao and Bryan, 2017;Cui et al., 2018). Being the country with the largest population and food consumption, China faces a series of problems, such as extensive management and low utilisation rate of water resource in agricultural production. (Khan et al., 2009;Kang et al., 2017). Previous studies on China have quantified the WF of crop production at the irrigation district scale (Sun et al., 2013;Cao et al., 2014;Sun et al., 2017), watershed scale (Zhuo et al., 2014;Zhuo et al., 2016b) and national scale (Zhuo et al., 2016a;Wang et al., 2019). Sun et al. (2013) found that the WF of crop depended on agricultural management rather than on regional climate differences; Zhuo et al. (2016a) showed that China's domestic food trade was determined by the economy and government policies, not by regional differences in water endowments; Wang et al. (2019) showed possibility and importance of accounting for developments of water-saving techniques in largescale crop WF estimations. However, most of these studies focused on quantifying WF from a single physical perspective. To our knowledge, there is no study yet to provide clear insights into the economic benefits of water use.

To fill the above research gap, the current study objective is, taking China over 2001-2016 as the study case, to explore the relationship between water resource consumption and economic value creation of intra-national scale crop production, and to propose a synergy evaluation index (SI) of PWF and EWF. First, the blue and green PWF (PWF_b, PWF_g) of 14 major crops (winter wheat, spring wheat, spring maize, summer maize, rice, soybean, cotton, groundnut, rapeseed, sugar beet, sugarcane, citrus, apple, and tobacco) is calculated annually in 31 provinces, and the corresponding EWF is derived. Second, crops are distinguished between grain and cash crops, with Mann-Kendall trend test and spatial autocorrelation analysis method for evaluation of the temporal and spatial evolution characteristics of PWF and EWF. Finally, the synergy evaluation index (SI) is constructed to reveal the synergies and trade-offs of crop water productivity and its economic value from the WF perspective.

2 Method and data

2.1 Calculation of production-based water footprint (PWF)

The PWF ($m^3\ kg^{-1}$) consists of the blue PWF (PWF_b, $m^3\ kg^{-1}$) and the green PWF (PWF_g, $m^3\ kg^{-1}$), which are respectively calculated from the daily green ($ET_{g[t]}$, mm) and blue evapotranspiration ($ET_{b[t]}$, mm) and crop yield (Y, kg ha^{-1}) during the growing period (Hoekstra et al., 2011), as shown in Eqs. (1) - (3):

$$PWF = PWF_b + PWF_g , \tag{1}$$

$$PWF_b = \frac{10 \times \sum_{t=1}^{gp} ET_{b[t]}}{Y} , \tag{2}$$

$$PWF_g = \frac{10 \times \sum_{t=1}^{gp} ET_{g[t]}}{Y} , \tag{3}$$

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. AquaCrop, a water-driven crop growth model developed by FAO, has fewer parameters for yield and water response studies than other crop growth models, and provides a better balance between simple, accuracy and robustness (Steduto et al., 2009). The simulated values of crop yield at each station obtained by the model are aggregated by province, and checked at the provincial scale by using national statistical data.

The dynamic soil water balance in the AquaCrop model is shown in Eq. (4):

$$S_{[t]} = S_{[t-1]} + PR_{[t]} + IRR_{[t]} + CR_{[t]} - ET_{[t]} - RO_{[t]} - DP_{[t]} , \tag{4}$$

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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):

$$RO_{[t]} = \frac{(PR_{[t]} - I_a)^2}{PR_{[t]} + S - I_a}, \tag{5}$$

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 ($m^3\ m^{-3}\ day^{-1}$). 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) and Zhuo et al. (2016b) combined with the model of soil water dynamic balance to separate the daily blue and green ET (mm), as shown in Eqs. (6) and (7):

$$S_{b[t]} = S_{b[t-1]} + IRR_{[t]} - RO_{[t]} \times \frac{IRR_{[t]}}{PR_{[t]} + IRR_{[t]}} - (DP_{[t]} + ET_{[t]}) \times \frac{S_{b[t-1]}}{S_{[t-1]}}, \tag{6}$$

$$S_{g[t]} = S_{g[t-1]} + IRR_{[t]} - RO_{[t]} \times \frac{IRR_{[t]}}{PR_{[t]} + IRR_{[t]}} - (DP_{[t]} + ET_{[t]}) \times \frac{S_{g[t-1]}}{S_{[t-1]}}, \tag{7}$$

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 and Döll (2010), the maximum soil moisture of rainfed fallow land two years before planting is taken as the initial soil moisture for simulating. At the same time, the initial soil water during the growing period is set as green water (Zhuo et al., 2016b).

2.2 Calculation of economic value-based water footprint (EWF)

Following Hoekstra et al. (2011), the EWF ($m^3\ USD^{-1}$) of crop production represents the water consumption per unit of economic value.

$$EWF = \frac{PWF}{UP}, \tag{8}$$

where PWF ($m^3\ kg^{-1}$) the production-based WF, and UP ($USD\ kg^{-1}$) the crop unit price. 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 conditions by the unit price of crops, as shown in Eq. (9). 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. (10) - (12):

$$EWF_{g,rf} = \frac{CWU_{g,rf}}{Y_{RF} \times UP}, \tag{9}$$

$$\alpha = \frac{Y_{irr} - Y_{rf}}{Y_{irr}}, \tag{10}$$

$$EWF_{b,ir} = \frac{CWU_{b,ir}}{Y_{IR} \times UP \times \alpha}, \tag{11}$$

$$EWF_{g,ir} = \frac{CWU_{g,ir}}{Y_{IR} \times UP \times (1-\alpha)}, \tag{12}$$

where $CWU_{g,rf}$ (m^3 ha^{-1}) represents the consumption of green water per unit area in rainfed agriculture; $CWU_{b,ir}$ (m^3 ha^{-1}) and $CWU_{g,ir}$ (m^3 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 actual crop yield under the rainfed and irrigation mode, respectively; Y_{rf} and Y_{ir} represent the model simulated yield under the rainfed and irrigation mode, 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.

2.3 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 H_0 is the that all variables in WF time series $\{WF_i \mid i = 1, 2, ..., 16\}$ are independent and identical in distribution, with no variation trend; the alternative hypothesis H_1 is that all i，$j \le 16$ and $i \ne j$, 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. (13)：

$$S=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn(WF_j-WF_i)\,, \tag{13}$$

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. (14).

$$sgn(\theta)=\begin{cases}1 & \theta>0\\ 0 & \theta=0\\ -1 & \theta<0\end{cases}. \tag{14}$$

When $n \geq 8$, the M-K statistic S roughly follows a normal distribution, whose mean value is zero, and the variance can be calculated by Eq. (15).

$$Var(S)=\frac{n(n-1)(2n+5)-\sum_{p=1}^{g}t_p(t_p-1)(2t_p+5)}{18}\,, \tag{15}$$

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. (16).

$$Z_c=\begin{cases}(S-1)/\sqrt{Var(S)} & S>0\\ 0 & S=0\\ (S+1)/\sqrt{Var(S)} & S<0\end{cases}. \tag{16}$$

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. (17).

$$I=\frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}(WF_i-\overline{WF})(WF_j-\overline{WF})}{\sum_{j=1}^{n}(WF_i-\overline{WF})^2\sum_{i=1}^{n}\sum_{j=1}^{n}W_{ij}}\,, \tag{17}$$

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 significantly positive, it indicates that provinces with similar geographical attributes are clustered in space. On the contrary, if the Global Moran's I is significantly negative, it means that provinces with different geographical attributes are clustered in space. Local Moran index (LISA) (Anselin, 1995) is used to detect whether there is local clustering of attributes, and the level (high or low) of the WF of a province is shown by the LISA cluster map. The LISA cluster map contains four types (Anselin, 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 opposite to adjacent provinces. The analysis of spatial autocorrelation can be realised by GeoDa.

2.4 The synergy evaluation index (SI) of PWF and EWF

To conduct a comprehensive assessment of WF from a physical and economic perspective, we compared provincial PWF and EWF with the respective average at the national level, and the sum of the ratios of the differences to the ranges is the synergy evaluation index (SI) of this province. The SI is calculated as follows:

$$SI_{i,j,c} = \frac{\overline{PWF_{j,c}} - PWF_{i,j,c}}{PWF_{j,c,max} - PWF_{j,c,min}} + \frac{\overline{EWF_{j,c}} - EWF_{i,j,c}}{EWF_{j,c,max} - EWF_{j,c,min}}, \tag{18}$$

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 USD^{-1}) are the averages at the national level in year j. Obviously, $-2 \leq SI_{i,j,c} \leq 2$. 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. The greater the SI, the more advantageous the region is in terms of water resource consumption and economic value creation in crop production (less water consumption per yield and higher economic benefits per water consumption unit). On the contrary, a low SI indicates that the contradiction between water resource consumption and economic value creation in crop production is sharp (more water consumption per yield but lower economic benefits per unit water consumption).

2.5 Data

The planting area and yield data of each province was 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 price using the inflation rate based on 2001. The consumer price index (CPI), which is used to calculate the inflation rate, was retrieved from NBSC (2019). The exchange rate used to convert local constant prices into American constant prices was taken from The World Bank (2019). The meteorological data on daily precipitation, daily mean maximum temperature and daily mean minimum temperature required for the Aquacrop model of 698 meteorological stations in the study area were downloaded from CMDC (2019). The irrigation and rainfed areas of crops were retrieved from MIRCA2000 (Portmann et al., 2010). The soil texture data was taken from the ISRIC database (Dijkshoorn et al., 2008). The soil water content data was from Batjes (2012); The date of planting of crops refers to (Chen et al., 1995). The harvest index was taken from Xie et al. (2011) and Zhang and Zhu (1990). Crop growth period and maximum root depth were taken from Allen et al. (1998) and Hoekstra and Chapagain (2007).

Figure 1. Considered weather stations across mainland China.

3 Results

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 $m^3 kg^{-1}$ to 0.93 $m^3 kg^{-1}$ (Fig. 2a); and the PWF of cash crop decreased by 35% from 0.70 $m^3 kg^{-1}$ to 0.46 $m^3 kg^{-1}$ (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.

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

Table 1 lists the PWF and composition of blue and green water by crops in 2001 and 2016. 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 $m^3 kg^{-1}$ in 2016). Among cash crops, cotton had the highest PWF (3.68 $m^3 kg^{-1}$ in 2016), while sugar beet consumed the least water per yield (0.06$m^3 kg^{-1}$ in 2016). Among grain crops, the proportion of blue WF in spring wheat was the highest (69% in 2016) and the proportion of blue WF in soybean was the smallest (20% in 2016). Cotton had the highest proportion of blue WF (32% in 2016) in cash crops. Winter wheat is the grain crop with the highest output in China, and its PWF decreased by 29% (from 1.47 $m^3 kg^{-1}$ in 2001 to 1.04 $m^3 kg^{-1}$ in 2016). Cotton is the cash crop with the highest water consumption per yield, and its PWF decreased by 31% (from 5.29 $m^3 kg^{-1}$ in 2001 to 3.68 $m^3 kg^{-1}$ in 2016). The M-K test results of each crop's PWF in table 2 further confirm the above views. Among them, the M-K statistical values of the PWF of cash crops all passed the significance level test of $p<0.05$.

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Table 1. National average production-based water footprint (PWF) of crops in China for the years 2001 and 2016.

Table 2. M-K analysis of production-based water footprint (PWF) of the 14 crops.

Figure 3a and 3b show the spatial distribution of PWF of grain and cash crops across 31 provinces, respectively, in four representative years (2001, 2006, 2011 and 2016). The PWF of grain crop was overall higher in northwest of China, represented by provinces Shaanxi, Gansu, Inner Mongolia and Ningxia, with the phenomenon of clustered distribution. The south-eastern coastal areas such as Guangdong, Fujian and Zhejiang were at a relatively low level. Consistently with the national level analysis, the PWF of the 31 provinces decreased significantly over time (Figure 3a). Specifically, in north-western China, Gansu province, where the water-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 $m^3\ kg^{-1}$) and showed an obvious downward trend, which decreased by 30% from 1.73 $m^3\ kg^{-1}$ in 2001 to 1.21 $m^3\ kg^{-1}$ in 2016. Concerning the composition of blue and green water, Xinjiang had the largest proportion 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%.

Differently from grain crop, the PWF of cash crop was higher in the Beijing-Tianjin-Hebei region and the western provinces, and lower in Inner Mongolia province and the southern coastal areas, without an obvious clustered characteristic (Figure 3b). Specifically, during the study period, the PWF of cash crop in Tianjin where cotton was the main cash crop was the largest (3.31 $m^3\ kg^{-1}$ in 2011, much higher than the national level of 0.51 $m^3\ kg^{-1}$ the same year), with the annual average of 2.90 $m^3\ kg^{-1}$. The PWF of cash crop in Guangxi where citrus and sugarcane were dominant was the smallest, with annual average of 0.14 $m^3\ kg^{-1}$, much lower than the national level of 0.54 $m^3\ kg^{-1}$. Concerning the composition of blue and green water, the proportion of blue water was larger in northern and north-eastern China, and lower in southern and southwestern China. Among them, the proportion of blue water of cash crop was the largest in Jilin province, with annual average of 35%, while the proportion of blue water in Qinghai province was less than 1%, which was the lowest in China. These results can be explained by the fact that Jilin's main cash crop was groundnut (88% in 2016), with high proportion of blue water consumption, while Qinghai's 99% of cash crops was rainfed rapeseed.

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

Table 3 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.

Table 3. Moran's I test for production-based water footprint (PWF) of crop production.

The LISA cluster map shows that the H-H regions of PWF of grain crop gathered in Gansu, Ningxia, Shaanxi and Inner Mongolia, and the L-L regions gathered in Guangdong, Zhejiang, Fujian, and Jiangxi (Fig. 4a). At the beginning of the study period, the PWF in 2001 showed an obvious positive spatial correlation, with 13 significant provinces (Gansu, Ningxia, Shaanxi, Inner Mongolia, and Hebei in H-H regions; Guangdong, Zhejiang, Fujian, Jiangxi, Anhui, Jiangsu, and Hunan 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 agglomeration of PWF of grain crop decreased with time. As for cash crop, no obvious agglomeration existed (Fig. 4b).

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

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 m^3 USD^{-1} to 5.04 m^3 USD^{-1} (Figure 5a); the EWF of cash crop decreased by 62%, from 5.39 m^3 USD^{-1} to 2.05 m^3 USD^{-1} (Fig. 5b).

In terms of grain crop, the $EWF_{b,ir}$ fluctuated, reaching the highest value of 46 m^3 USD^{-1} in 2002 and falling to the lowest of 15.67 m^3 USD^{-1} in 2011. In contrast, the $EWF_{g,ir}$ and $EWF_{g,rf}$ showed a significant and steady declining trend, decreasing from 4.70 m^3 USD^{-1} and 10.11 m^3 USD^{-1} in 2001 to 2.72 m^3 USD^{-1} and 5.10 m^3 USD^{-1} in 2016, respectively. Among the three types of WF, the $EWF_{g,ir}$ was the lowest (mean 2.79 m^3 USD^{-1}), $EWF_{b,ir}$ was the highest (mean 23.68 m^3 USD^{-1}), and $EWF_{g,rf}$ (mean 5.60 m^3 USD^{-1}) was close to the average EWF (5.41 m^3 USD^{-1}) in irrigation and rainfed production mode. This suggests that more water was required per additional benefit unit under irrigation than under rainfed mode, whereas in the rainfed agriculture, compared with blue water, increasing the input of green water may result in more economic benefits. Therefore, utilisation efficiency of green water resource for grain crops should be improved.

Concerning cash crop, the $EWF_{b,ir}$ decreased by 62% from 14.39 m^3 USD^{-1} to 5.47 m^3 USD^{-1}. Compared to grain crop, the difference between the $EWF_{g,ir}$ and $EWF_{g,rf}$ was smaller, with average values of 2.60 m^3 USD^{-1} and 2.29 m^3 USD^{-1}, respectively. In addition, compared to grain crop, the EWF of cash crop was lower, which indicated that cash crop production could get more economic benefits per water consumption unit. Besides, increasing the input of green water resource could obtain higher economic benefits, and the rainfed production model had greater economic potential.

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

Table 4 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 (3.01 m^3 kg^{-1} in 2016), also had the highest EWF; the second most water-intensive, spring wheat (1.51 m^3 kg^{-1} in 2016) had the second highest EWF (8.03 m^3 USD^{-1} in 2016); rice, with the lowest water consumption per yield unit (0.78 m^3 kg^{-1} in 2016) also had the lowest EWF (3.39 m^3 USD^{-1} in 2016). Regarding cash crops, cotton, with the highest water consumption per yield unit (3.68 m^3 kg^{-1} in 2016) was the crop with the highest EWF (2.98 m^3 USD^{-1} in 2016); groundnuts' EWF ranked second (2.73 m^3 USD^{-1} in 2016); sugar beet had lowest water consumption per yield unit (0.06 m^3 kg^{-1} in 2016), with an EWF (1.57 m^3 USD^{-1} in 2016) much lower than the average EWF of cash crops (2.05 m^3 USD^{-1} in 2016).

Sugarcane had the lowest $EWF_{b,ir}$ (0.83 m^3 USD^{-1} in 2016). The difference between $EWF_{g,ir}$ and $EWF_{g,rf}$ of soybean was the largest, which were 4.97 m^3 USD^{-1} and 8.69 m^3 USD^{-1}, respectively, in 2016. The difference between $EWF_{g,ir}$ and $EWF_{g,rf}$ of tobacco was the smallest, which were 0.58 m^3 USD^{-1} and 0.83 m^3 USD^{-1}, respectively, in 2016. During the study period, the $EWF_{g,rf}$ of cash crops decreased most significantly. As for the $EWF_{b,ir}$, the downward trend of cash crops was more significant, compared to that of grain crops. The M-K test results in Table 7 further confirmed the above results, as the M-K statistical values of all crops' EWF passed the significance level test of $p<0.05$.

Table 4. National average economic value-based water footprint (EWF) of crops in China for the years 2001 and 2016.

Table 5. M-K analysis of economic value-based water footprint (EWF) of the 14 crops in China for 2001-2016.

Figure 6a and 6b show the spatial distribution of EWF of grain and cash crops, respectively. Generally, the EWF of grain crop was higher in north-western China, represented by Shaanxi, Gansu, Inner Mongolia, Ningxia and Xinjiang; Guangdong, Jiangxi, Fujian, Zhejiang and other south-eastern coastal provinces were at a relatively low level, 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. 10). Specifically, 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 the top three (mean 8.34 m^3 USD^{-1}), with a significant decline of 46% over time, from 13.28 m^3 USD^{-1} in 2001 to 7.12 m^3 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 m^3 USD^{-1} and 1.39 m^3 kg^{-1}) were second only to those in Gansu. In contrast, the EWF and PWF (mean 4.49 m^3 USD^{-1} and 0.94 m^3 kg^{-1}) in Fujian, with rice as the main grain crop (86% of all grain crops in 2016) were far lower than the national average (mean 5.41 m^3 USD^{-1} and 1.01 m^3 kg^{-1}).

Concerning the composition of blue and green water for grain crop, the $EWF_{b,ir}$ in north-western China was lower, while the $EWF_{g,ir}$ 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 $EWF_{g,ir}$ and $EWF_{g,rf}$ (mean 5.57 m^3 USD^{-1} and 8.16 m^3 USD^{-1}, respectively), while the $EWF_{b,ir}$ was only 7.08 m^3 USD^{-1}, far lower than the national average (23.68 m^3 USD^{-1}).

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Instead, the $EWF_{g,ir}$ and $EWF_{g,rf}$ in Yunnan were close to the national average level (2.79 m^3 USD^{-1} and 5.60 m^3 USD^{-1}), and $EWF_{b,ir}$ was the highest (50.55m^3 USD^{-1}). The EWF of cash crop had no obvious spatial clustered phenomenon, decreasing significantly over time in 31 provinces, which was consistent with the spatial evolution characteristics of the corresponding PWF previously discussed (Fig. 6b).

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

Table 6 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.

Table 6. Moran’s I test for economic value-based water footprint (EWF) of crop production.

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 mainly concentrated in Ningxia, Gansu, Shaanxi, Shanxi, Inner Mongolia, and L-L regions were mainly concentrated in Guangdong, Zhejiang, Fujian, Jiangxi. During the research period, the EWF of grain crop showed an obvious and stable positive spatial correlation. In 2001, there were 14 significant provinces, with seven provinces (Gansu, Ningxia, Shaanxi, Shanxi, Inner Mongolia, Hebei, and Henan) in H-H regions, and seven provinces (Guangdong, Zhejiang, Fujian, Jiangxi, Guangxi, Jiangsu and Hunan) in L-L regions. In 2016, there were 13 significant provinces, of which the H-H regions remained unchanged, and only Guangxi province left out of the L-L regions. Generally, the spatial agglomeration pattern of EWF of grain crop was stable. As for cash crop, the LISA maps of four representative years shows great changes. Only in 2011, it shows a certain positive spatial correlation, with 4 provinces (Hunan, Hubei, Chongqing and Guizhou) in H-H regions. Overall, the EWF of cash crop did not show obvious spatial agglomeration.

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

3.2 Synergy evaluation of PWF and EWF

Figure 8a and 8b show the SI between PWF and EWF of grain and cash crops across 31 provinces, respectively over years. Concerning grain crop, the number of provinces with negative SI were increasing. Over time, the areas with negative SI gradually expanded to the south. The SI was mostly negative in Beijing-Tianjin-Hebei, Inner Mongolia and north-western China. In 2016, the SI of Shaanxi was -1.13, the lowest in China. The SI of Jiangxi, Chongqing, Hubei, Hunan, Jiangsu, Zhejiang, Shanghai, and other coastal areas in south-eastern China was positive. In 2016, the SI of Jiangxi was 0.62, the highest in China. Overall, the SI of grain crop was negative in north-western China (Shaanxi, Gansu, Inner Mongolia, Ningxia), whereas in Guangdong, Jiangxi, Fujian, Zhejiang and other coastal areas in south-eastern China it was positive, with a clustered distribution.

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

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

Further, taking 2016 as an example, we further look at the reasons for the coordination contradiction between the PWF and EWF in both grain and cash crops (see Fig. 9), from the perspective of planting structure (see Fig. 10). In terms of grain crop, the PWF and EWF in 9 provinces (Shaanxi, Gansu, Shanxi, Tianjin, Inner Mongolia, Qinghai, Hebei, Xinjiang, and Ningxia) were significantly higher than the national average level; the PWF and EWF in Fujian, Guangdong, Hunan, Hubei and Jiangxi were significantly lower than the national average. Shaanxi province had the highest PWF in China (1.23 m^3 kg^{-1}), and the second highest EWF (7.48 m^3 USD^{-1}). In Shaanxi province, winter wheat and spring maize with high water consumption and low yield accounted for more than 90% of the total sown area of grain crops, with yields lower than the national averages by 24% and 26%, respectively. Moreover, the price of wheat in Shaanxi province (0.17 USD kg^{-1}) was lower than the national average (0.19 USD kg^{-1}). The reasons for high water consumption per unit of grain production coupled with 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 EWF were 0.77 m^3 kg^{-1} and 3.63 m^3 USD^{-1}, well below the national averages (0.93 m^3 kg^{-1}, 5.04 m^3 USD^{-1}).

As for cash crop, the PWF and EWF in 15 provinces, including Tianjin, Jilin and Jiangxi, were significantly higher than the national average values, while the PWF and EWF of the five provinces represented by Shanxi were lower than the national average level. The PWF of Tianjin was 1.92 m^3 kg^{-1}, the highest in China, and the EWF was 3.26 m^3 USD^{-1}, the fifth highest in China, which was significantly higher than the national average (2.05 m^3 USD^{-1}). It can be seen from Fig. 24 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. Large-scale planting of water-intensive crops sold at a low price led to high water consumption per yield but poor economic benefits in cash crop production in Tianjin. Jiangxi province showed the highest EWF in China (3.86 m^3 USD^{-1}), and a PWF (0.96 m^3 kg^{-1}) which was also higher than the national average (0.46 m^3 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). The low selling price and yield per unit area explain the poor economic benefits per water consumption unit in cash crop production in Jiangxi. In contrast to the situation of Tianjin and Jiangxi, 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 (18.8 t ha^{-1}). Therefore, the large-scale planting of low water consumption crops with high level of crop yield contributed to the higher economic benefits per water consumption unit displayed in cash crop production in Shanxi.

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.

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

4 Discussion

The goal of WF regulation is to reduce its magnitude to a sustainable level (Hoekstra, 2013), but the contradictions 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.

Table 7 compares the PWF results of crops production between the current study and previous ones. Differently from Mekonnen and Hoekstra (2011) and Zhuo et al. (2016a), this study distinguishes between wheat and maize varieties when calculating the WF, despite China's wheat production is mainly of winter wheat (accounting for 95% in 2016). Due to the differences of varieties, water consumption intensity and planting conditions, it is necessary to distinguish between crops in the provinces where spring wheat is the main crop. In addition, due to the differences in model selection and parameters, the calculation results will also be different. For example, Mekonnen and Hoekstra (2011) used CROPWAT model and checked the crop yield at the national scale, while this study chooses AquaCrop model and checks the crop yield at the provincial level. Both the studies of Mekonnen and Hoekstra (2011) and Zhuo et al. (2016a) were based on the 5 arc-minute grid, while this

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research calculates the WF based on the meteorological station scale. In general, however, the crop production WF in this study is close to that of previous studies, which shows the rationality of the calculated results.

Table 8 compares the EWF of this study with previously calculated results of the economic water productivity. 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 unit and price unit, 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).

Moreover, the SI results showed that the economic benefits of blue water and green water differed greatly. As for grain production at the national level, the $EWF_{b,ir}$ (mean 23.68 m^3 USD^{-1}) was much higher than the $EWF_{g,ir}$ (mean 2.79 m^3 USD^{-1}), and the $EWF_{g,rf}$ (mean 5.60 m^3 USD^{-1}) was the closest to the average EWF in irrigation and rainfed agriculture (mean 5.41 m^3 USD^{-1}). Compared with grain crops, the difference between $EWF_{g,ir}$ and $EWF_{g,rf}$ of cash crops was smaller, with average values of 2.60 m^3 USD^{-1} and 2.29 m^3 USD^{-1}, respectively. Moreover, the EWF of cash crops 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 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 southern China, the $EWF_{b,ir}$ was higher, while the $EWF_{g,ir}$ and $EWF_{g,rf}$ were lower. Therefore, the utilisation efficiency of green water resources should be improved, rainwater collection and storage should be developed, and the proportion of green water in the acquisition of irrigation water should be increased. As for northern China, green water (rain water) should be converted into blue water (irrigation water) as far as possible, so as to reduce blue water consumption while ensuring and increasing economic benefits. As for southern China, rainfed agriculture should be chosen as far as possible. The necessary way to alleviate the contradiction between water resource consumption and economic value creation is to adjust the agricultural production mode and the irrigation method according to local conditions.

There was a serious incongruity between water consumption for crop production and economic value creation 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 contradiction 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. Therefore, the government should adjust the planting structure appropriately according to local conditions, reduce the crops requiring high water consumption and generating poor economic benefits in non-main producing areas, and regulate crop prices rationally, to balance the economic benefits of the water-intensive crops in different regions.

The study reveals the synergies and trade-offs of crop water productivity and its economic value from the perspective of WF. However, it is undeniable that there are some limitations and shortcomings. Firstly, in the calculation of WF, although the accuracy of AquaCrop model in simulating crop water consumption and yield, soil field water, and fertiliser management types under different climatic conditions has been widely demonstrated, the uncertainty of results caused by the uncertainty of input parameters must be acknowledged (Zhuo et al., 2014). Secondly, this paper does not make a specific distinction between crop irrigation methods. In fact, the difference of WF results caused by different irrigation methods cannot be ignored (Wang et al., 2019). Thirdly, when calculating the WF, it is assumed that the change of crop irrigation and rainfed planting area only occurs in the data grid based on 2000, and the migration of crop harvesting zone is not considered. Finally, this study does not focus specifically on the effects of field water and fertiliser management measures. Although there are restrictions on the availability of crop price unit data in the selection of research objects, it is still representative because the crops selected in this paper accounts for more than 85% of the national crop production. As for the study perspective, this article focuses on contradictions between water consumption and economic value creation in crop production. In fact, the ecological impacts on the environment cannot be ignored. Therefore, further research is expected to tackle this limitation by including the ecological impacts on the environment in a more comprehensive assessment.

Table 7. Comparison between production-based water footprint (PWF) of crops production in mainland China in the current study and previous studies.

Table 8. Comparison between economic value-based water footprint (EWF) in the current results and previous studies.

5 Conclusions

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:

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

(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 contradiction has 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 incongruity 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.

Data availability

Data sources of carrying out the study are listed in the section 2.5 Data. Data generated in this paper is available by contacting L Zhuo.

Author contributions

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

Competing interests

The authors declare that they have no conflicts of interests.

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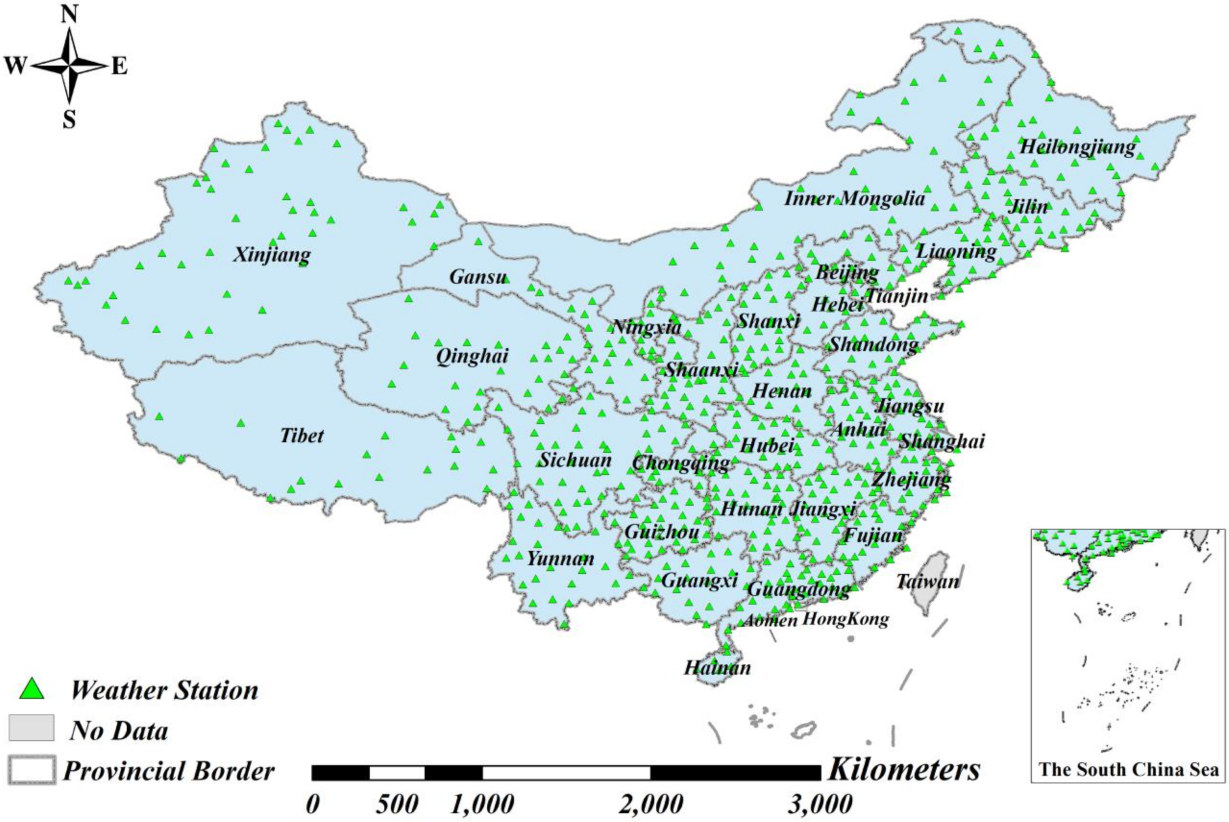

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631 **Figure 1: Considered weather stations across mainland China.**

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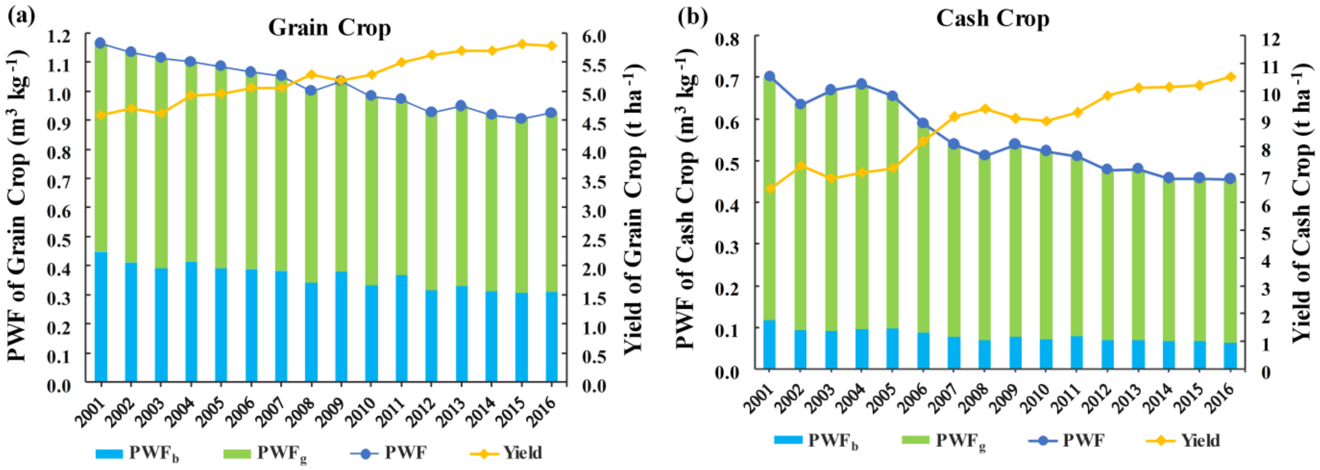

634 **Figure 2: Interannual variability of national average production-based water footprint (PWF) of (a) grain and (b) cash crops in**
635 **China over 2001-2016.**

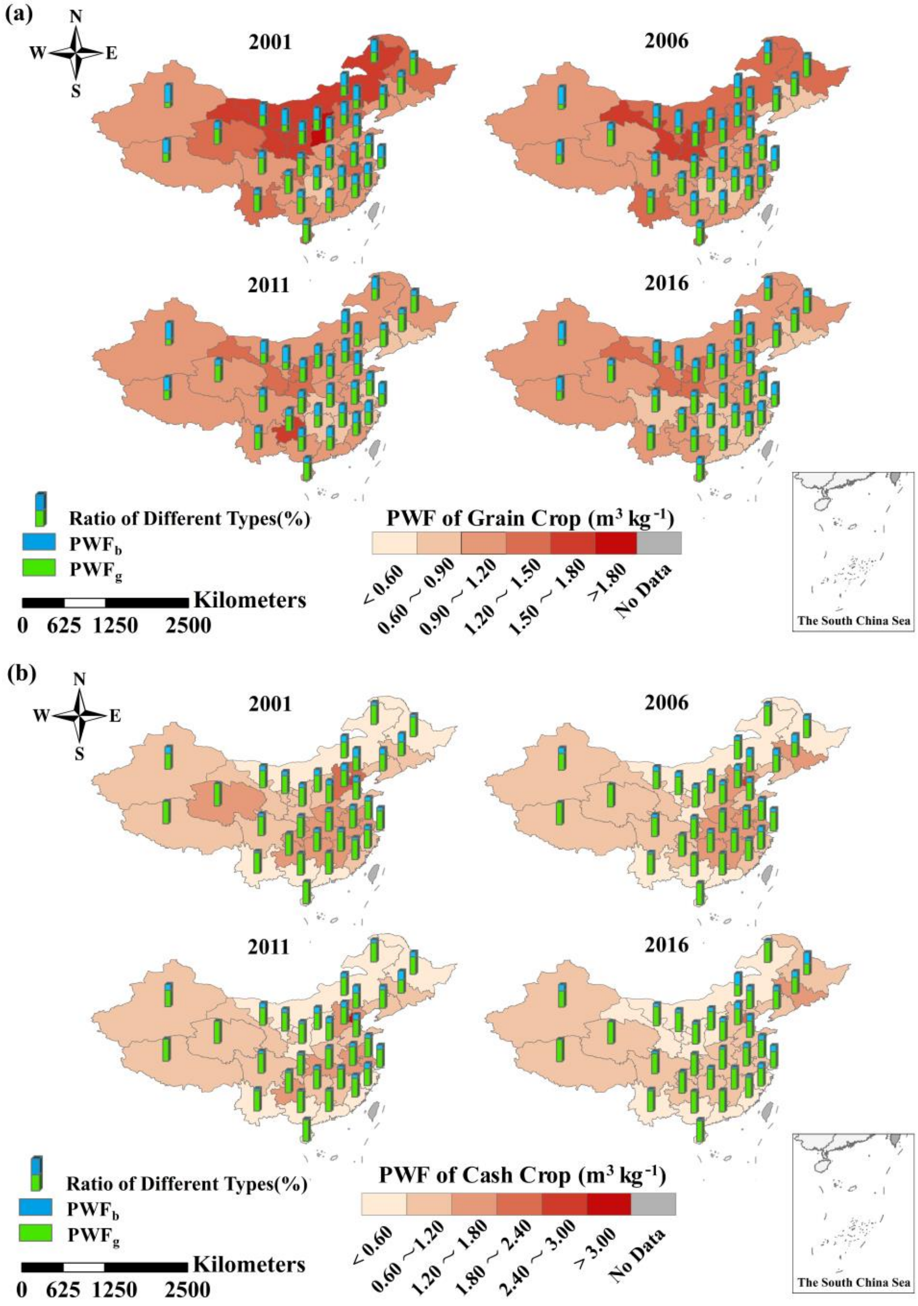

Figure 3: Temporal and spatial evolution of production-based water footprint (PWF) of (a) grain and (b) cash crops in China.

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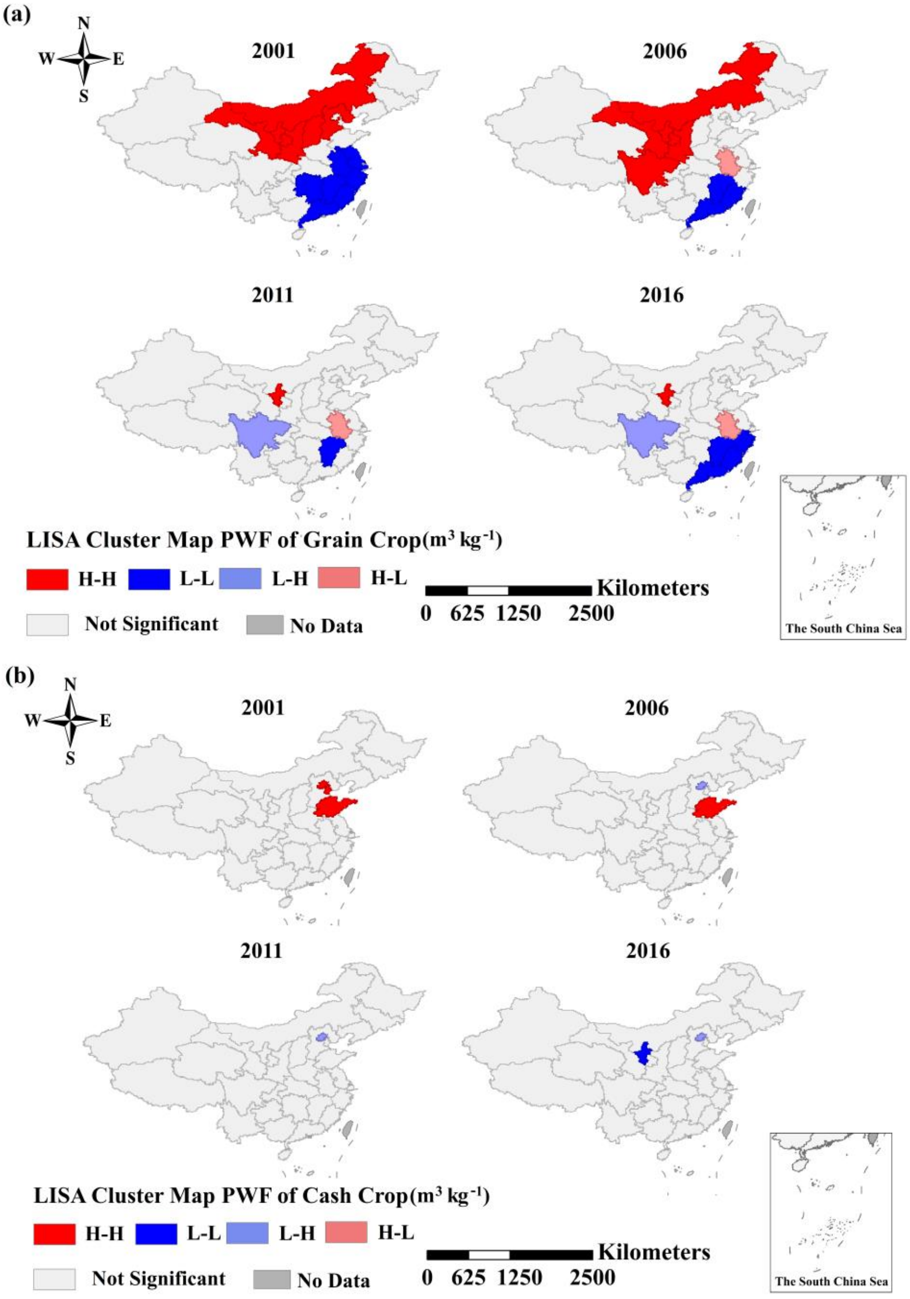

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639 **Figure 4: The LISA cluster maps of production-based water footprint (PWF) of (a) grain and (b) cash crops.**

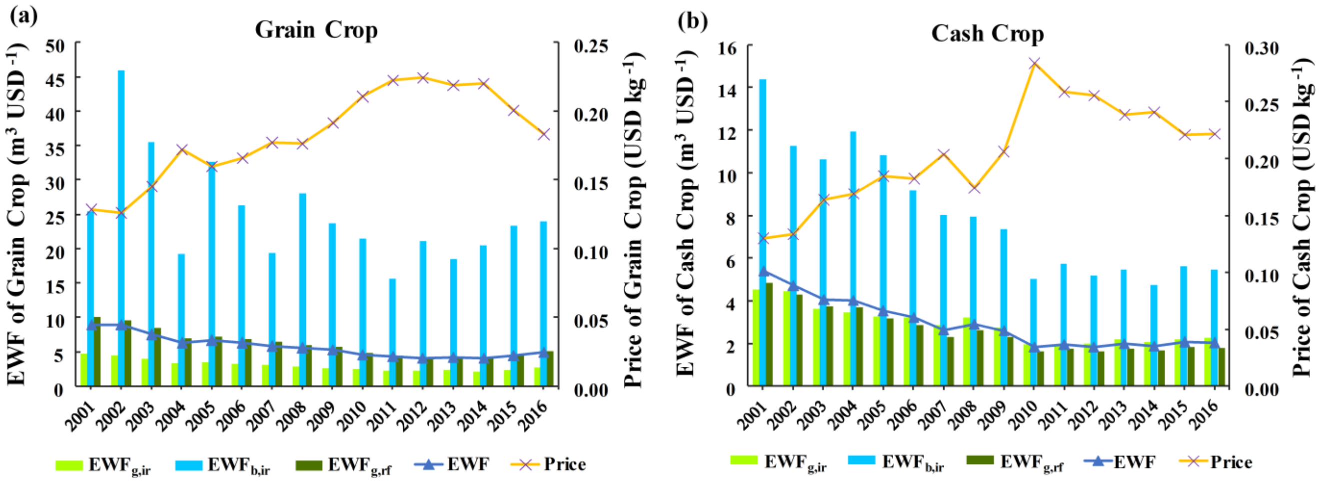
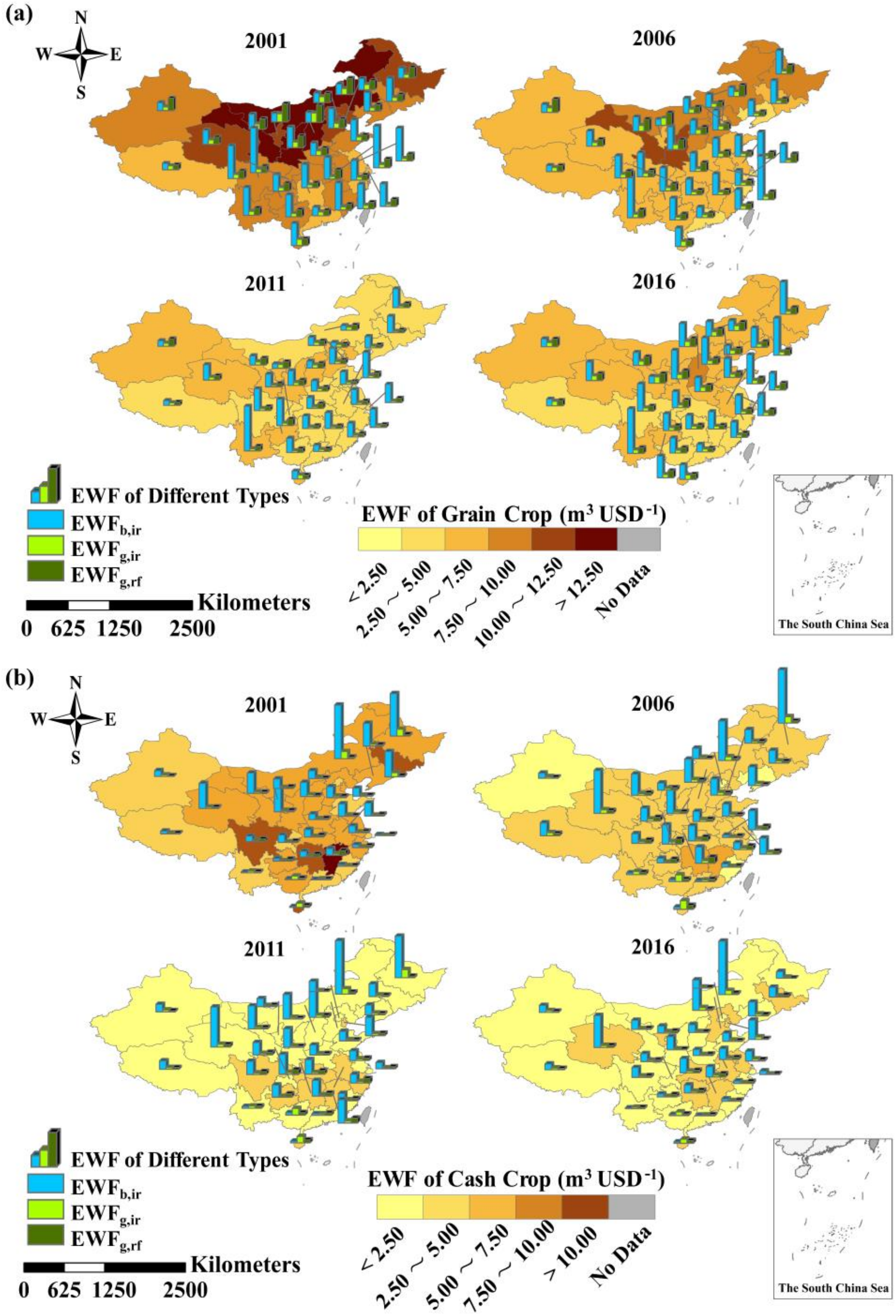


Figure 5: Interannual variability of economic value-based water footprint (EWF) of (a) grain and (b) cash crops in China over 2001-2016.



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

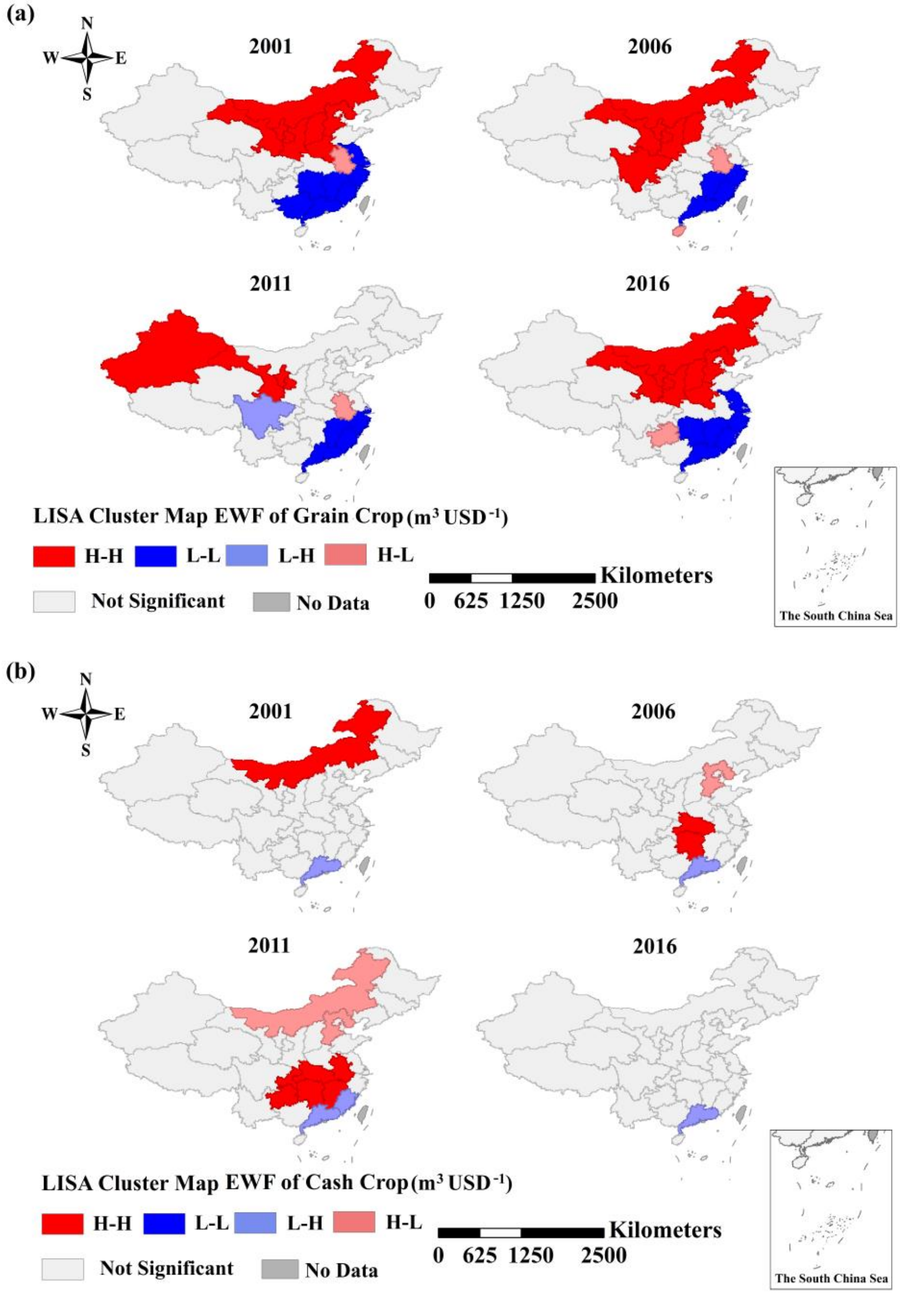

Figure 7: The LISA cluster maps of economic value-based water footprint (EWF) of (a) grain and (b) cash crops.

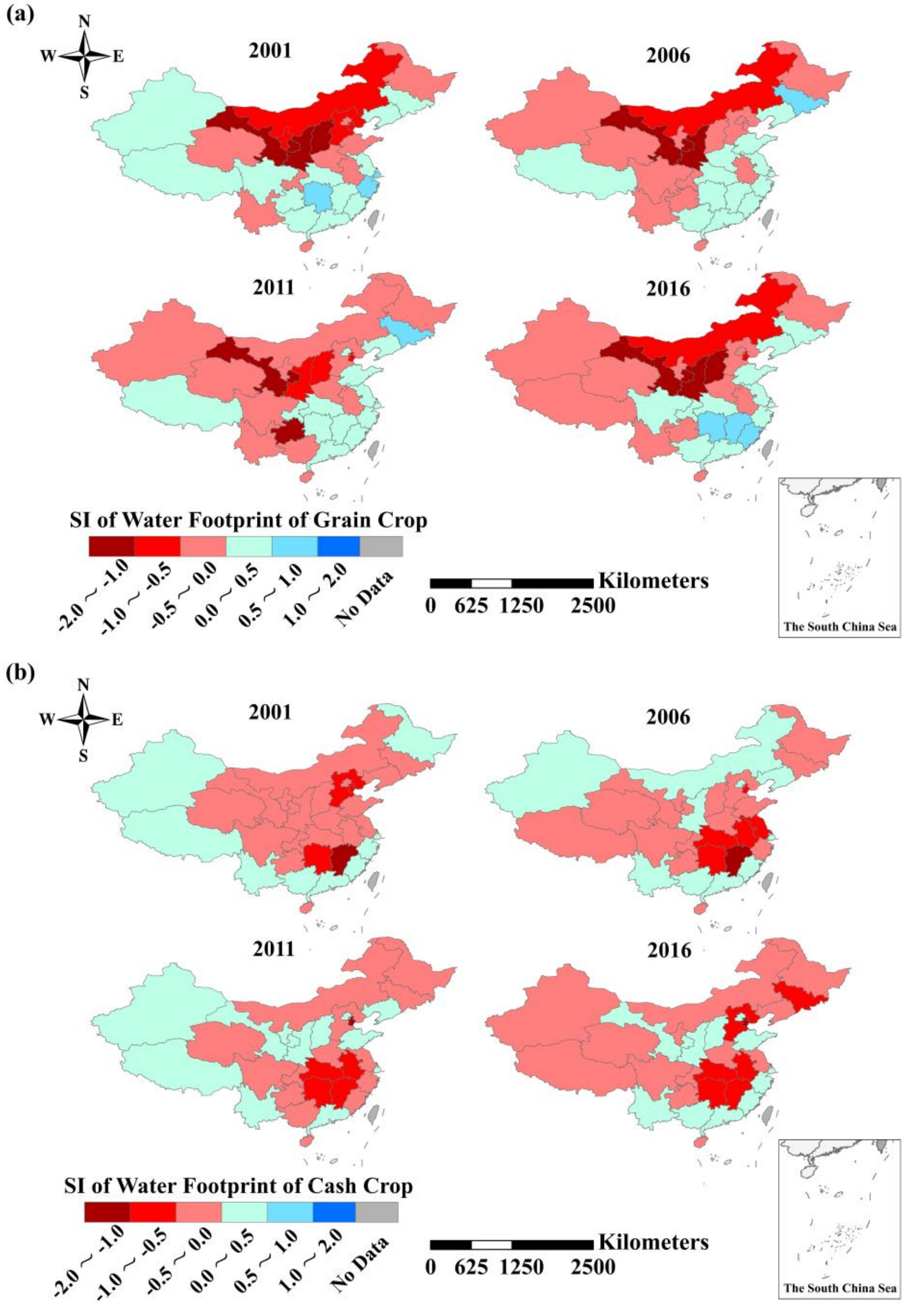

Figure 8: Temporal and spatial evolution of synergy evaluation index (SI) of (a) grain and (b) cash crops.

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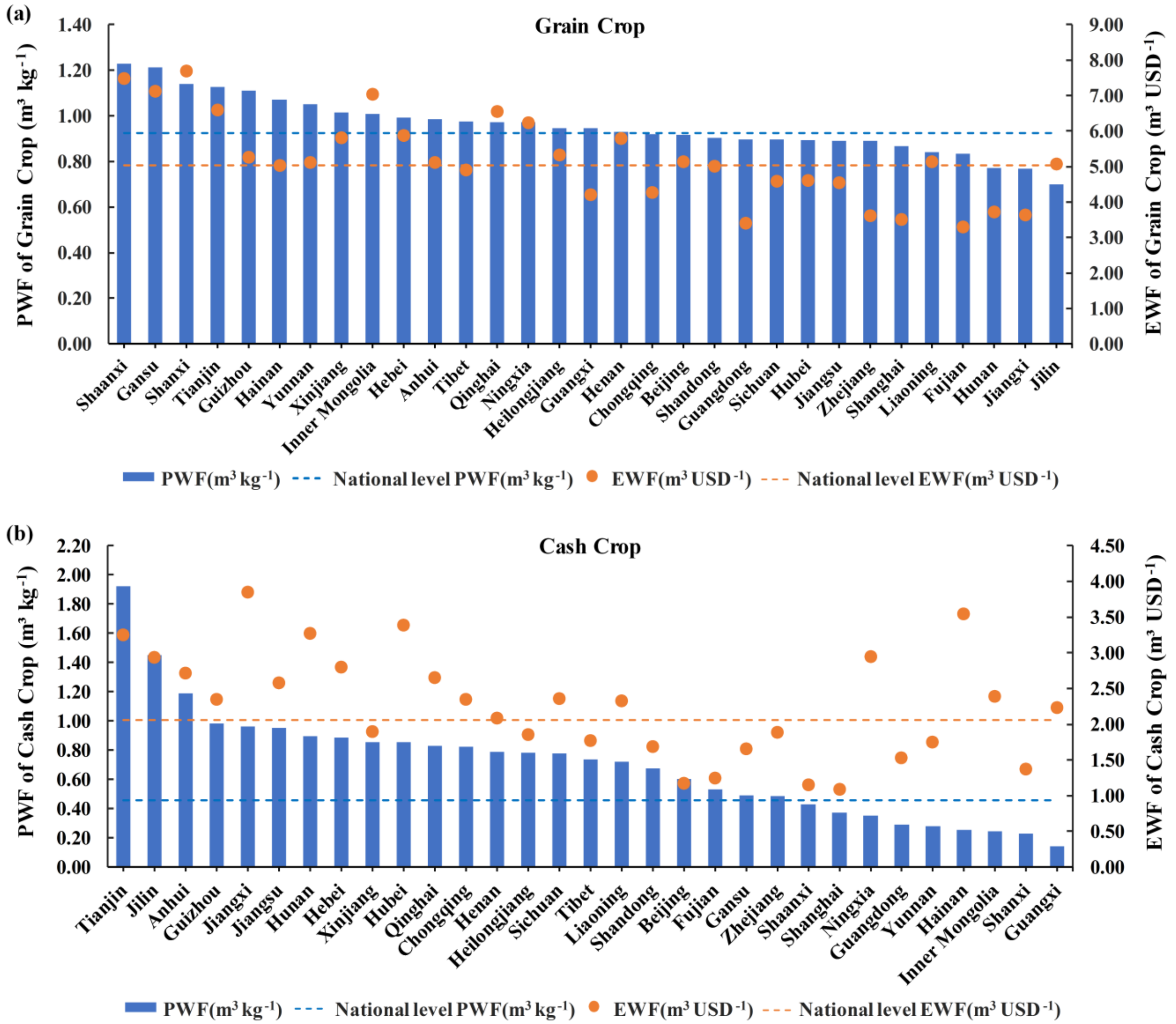

Figure 9: Production-based water footprint (PWF) versus economic value-based water footprint (EWF) of (a) grain and (b) cash crops per province in 2016.

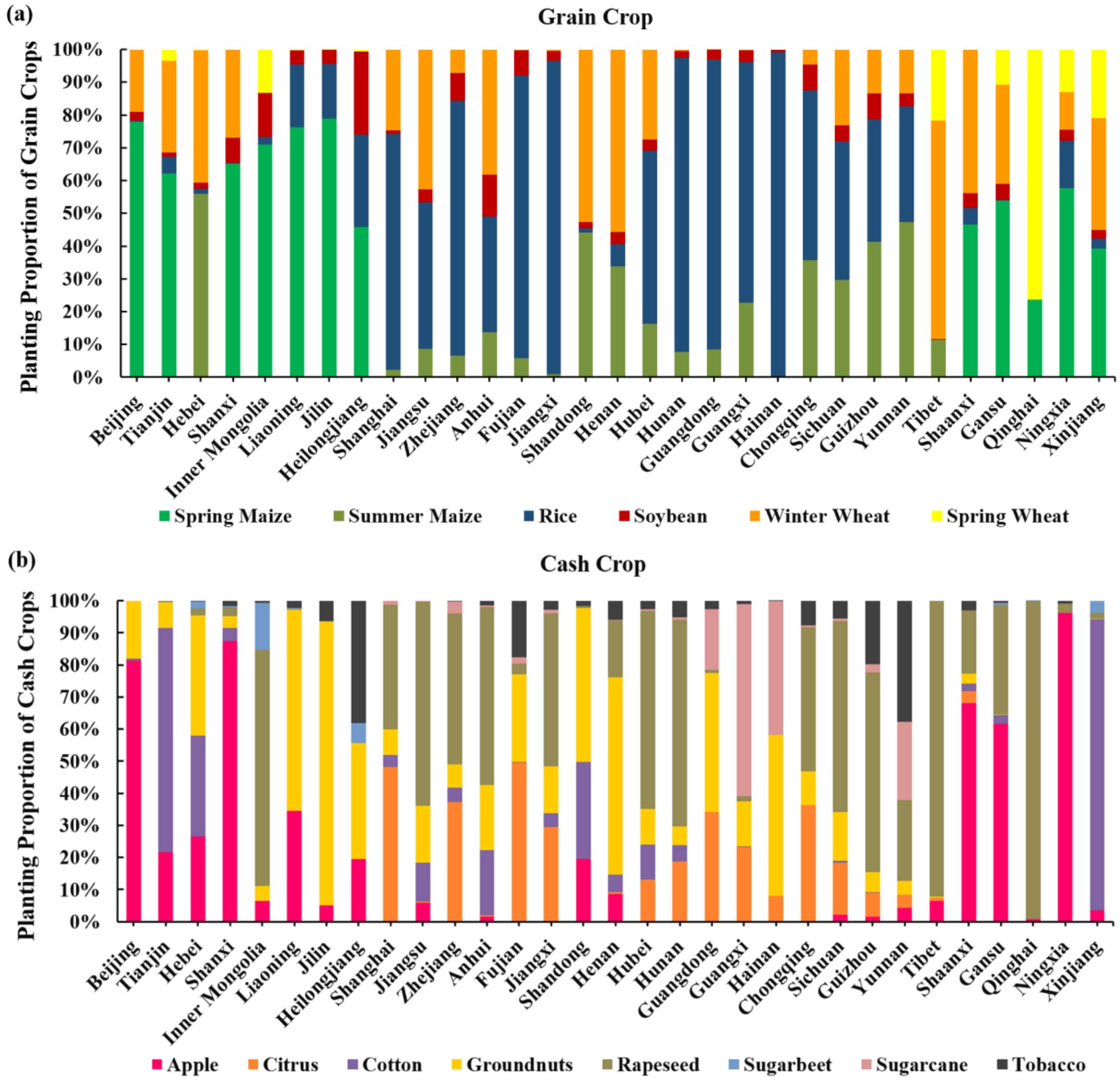

Figure 10: Planting structure of (a) grain and (b) cash crops in 31 provinces in 2016.

Table 1. National average production-based water footprint (PWF) of crops in China for the years 2001 and 2016.

	2001				2016			
	PWF_b m^3kg^{-1}	PWF_g m^3kg^{-1}	PWF m^3kg^{-1}	Yield $t\ ha^{-1}$	PWF_b m^3kg^{-1}	PWF_g m^3kg^{-1}	PWF m^3kg^{-1}	Yield $t\ ha^{-1}$
Grain Crop	0.45	0.71	1.16	4.60	0.32	0.61	0.93	5.78
Winter Wheat	0.63	0.84	1.47	3.81	0.40	0.64	1.04	5.40
Spring Wheat	-	-	-	-	1.05	0.46	1.51	4.24
Spring Maize	0.45	0.72	1.17	4.67	0.22	0.60	0.82	6.44
Summer Maize	0.32	0.78	1.10	4.73	0.22	0.72	0.94	5.44
Rice	0.39	0.46	0.85	6.16	0.32	0.46	0.78	6.86
Soybean	0.61	2.40	3.01	1.62	0.57	2.22	2.79	1.80
Cash Crop	0.12	0.58	0.70	6.51	0.07	0.39	0.46	10.53
Groundnuts	0.47	1.31	1.78	2.89	0.32	1.18	1.50	3.66
Rapeseed	0	1.29	1.29	1.60	0	1.04	1.04	1.98
Cotton	1.31	3.98	5.29	1.11	1.16	2.52	3.68	1.58
Sugarcane	0.01	0.12	0.13	60.63	0.01	0.09	0.10	74.55
Sugarbeet	0	0.14	0.14	26.81	0	0.06	0.06	57.70
Apple	0.06	0.51	0.57	9.69	0.03	0.28	0.31	18.88
Citrus	0.15	0.75	0.90	8.77	0.04	0.50	0.54	14.70
Tobacco	0.26	1.93	2.19	1.75	0.23	1.67	1.90	2.14

Table 2. M-K analysis of production-based water footprint (PWF) of the 14 crops.

		PWF (m^3kg^{-1})	**PWF_b (m^3kg^{-1})**	**PWF_g (m^3kg^{-1})**	**Yield ($t\ ha^{-1}$)**
Winter Wheat	Z_c	-4.547	-3.737	-4.547	5.178
	Signific	**	**	**	**
Spring Wheat	Z_c	-2.476	-0.135	-3.107	4.457
	Signific	*		**	**
Spring Maize	Z_c	-4.097	-4.097	-2.476	3.647
	Signific	**	**	*	**
Summer Maize	Z_c	-3.287	-3.647	-3.197	4.277
	Signific	**	**	**	**
Rice	Z_c	-3.377	-3.107	-3.017	4.637
	Signific	**	**	**	**
Soybean	Z_c	-0.675	1.846	-1.396	1.126
	Signific				
Groundnuts	Z_c	-3.917	-3.467	-3.287	4.547
	Signific	**	**	**	**
Rapeseed	Z_c	-2.476	2.386	-2.476	4.097
	Signific	*	*	*	**
Cotton	Zc	-4.007	0	-4.187	4.277
	Signific	**		**	**
Sugarcane	Z_c	-2.476	-3.377	-2.116	3.467
	Signific	*	**	*	**
Sugarbeet	Z_c	-4.457	-0.045	-4.457	4.727
	Signific	**		**	**
Apple	Z_c	-4.997	-4.907	-5.088	5.358
	Signific	**	**	**	**
Citrus	Z_c	-4.997	-4.997	-4.817	5.178
	Signific	**	**	**	**
Tobacco	Z_c	-2.746	-0.855	-2.836	2.926
	Signific	**		**	**

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

661 **Table 3. Moran's I test for production-based water footprint (PWF) of crop production.**

		Moran's *I*	***Z*-score**	***p*-value**
Grain Crop PWF ($m^3 kg^{-1}$)	**2001**	0.559	5.141	0.001
	2006	0.227	2.207	0.014
	2011	0.126	1.491	0.077
	2016	0.214	2.085	0.021
	2001-2016	0.263	2.659	0.009
Cash Crop PWF ($m^3 kg^{-1}$)	**2001**	0.302	2.972	0.004
	2006	0.152	1.665	0.052
	2011	0.094	1.252	0.106
	2016	0.11	1.224	0.11
	2001-2016	0.163	1.756	0.05

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Table 4. National average economic value-based water footprint (EWF) of crops in China for the years 2001 and 2016.

	2001					**2016**				
	$EWF_{b,ir}$ m ^{3}USD^{-1}	**$EWF_{g,ir}$ m ^{3}USD^{-1}**	**$EWF_{g,rf}$ m ^{3}USD^{-1}**	**EWF m ^{3}USD^{-1}**	**Price USD kg^{-1}**	**$EWF_{b,ir}$ m ^{3}USD^{-1}**	**$EWF_{g,ir}$ m ^{3}USD^{-1}**	**$EWF_{g,rf}$ m ^{3}USD^{-1}**	**EWF m ^{3}USD^{-1}**	**Price USD kg^{-1}**
Grain Crop	25.47	4.70	10.11	9.01	0.13	23.93	2.72	5.10	5.04	0.18
Winter Wheat	28.80	6.37	11.67	11.59	0.13	22.27	2.98	5.46	5.55	0.19
Spring Wheat	-	-	-	-	-	12.91	3.97	6.95	8.03	
Spring Maize	18.21	5.38	9.85	10.02	0.12	20.78	3.23	6.21	6.37	0.13
Summer Maize	36.17	5.55	9.19	9.44		54.30	4.39	6.95	7.28	
Rice	32.13	3.55	6.25	6.63	0.13	26.69	1.92	3.11	3.39	0.23
Soybean	22.68	7.53	13.33	12.83	0.23	30.38	4.97	8.69	8.69	0.32
Cash Crop	14.39	4.51	4.84	5.39	0.13	5.47	2.25	1.81	2.05	0.22
Groundnuts	24.50	3.72	5.71	6.37	0.28	16.14	1.74	2.57	2.73	0.54
Rapeseed			5.96	5.96	0.22			2.73	2.73	0.38
Cotton	20.03	3.06	5.30	5.79	0.91	6.54	2.32	2.48	2.98	1.23
Sugarcane	2.23	9.68	5.96	5.46	0.02	0.83	4.39	2.57	2.40	0.04
Sugar beet			5.38	5.38	0.03			1.57	1.57	0.04
Apple	57.61	2.73	4.47	4.72	0.12	13.82	0.66	1.16	1.16	0.26
Citrus	35.26	3.72	5.55	5.71	0.16	17.05	1.32	1.99	1.99	0.27
Tobacco	30.87	1.57	2.32	2.40	0.90	53.39	0.58	0.83	0.83	2.21

Table 5. M-K analysis of economic value-based water footprint (EWF) of the 14 crops in China for 2001-2016.

		EWF ($m^3 USD^{-1}$)	**EWF$_{b,ir}$** ($m^3 USD^{-1}$)	**EWF$_{g,ir}$** ($m^3 USD^{-1}$)	**EWF$_{g,rf}$** ($m^3 USD^{-1}$)	**Price** ($USD\ kg^{-1}$)
Winter Wheat	Z_c	-4.547	-2.116	-4.637	-4.547	4.007
	Signific	**	*	**	**	**
Spring Wheat	Z_c	-2.746	-0.585	-3.017	-2.746	4.007
	Signific	**		**	**	**
Spring Maize	Z_c	-3.647	-1.486	-3.557	-3.647	3.107
	Signific	**		**	**	**
Summer Maize	Z_c	-3.377	-0.675	-3.737	-3.467	3.107
	Signific	**		**	**	**
Rice	Z_c	-4.367	-1.486	-3.827	-4.277	3.647
	Signific	**		**	**	**
Soybean	Z_c	-2.116	1.396	-2.386	-2.296	2.116
	Signific	*		*	*	*
Groundnuts	Z_c	-3.377	-2.566	-3.107	-3.197	2.926
	Signific	**	*	**	**	**
Rapeseed	Z_c	-3.377	-3.287	-3.377	-3.377	3.197
	Signific	**	**	**	**	**
Cotton	Zc	-2.476	-3.827	-0.765	-2.926	0.135
	Signific	*	**		**	
Sugarcane	Z_c	-3.557	-4.187	-3.557	-3.557	3.017
	Signific	**	**	**	**	**
Sugar beet	Z_c	-4.457	-3.557	-2.476	-4.457	3.647
	Signific	**	**	*	**	**
Apple	Z_c	-3.557	-3.467	-3.557	-3.557	3.197
	Signific	**	**	**	**	**
Citrus	Z_c	-3.737	-1.666	-3.647	-3.647	1.576
	Signific	**		**	**	
Tobacco	Z_c	-4.817	-0.495	-4.817	-4.817	4.817
	Signific	**		**	**	**

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

669 **Table 6. Moran's I test for economic value-based water footprint (EWF) of crop production.**

		Moran's *I*	***Z*-score**	***p*-value**
Grain Crop EWF (m^3 USD^{-1})	**2001**	0.585	5.392	0.001
	2006	0.395	3.887	0.001
	2011	0.311	3.073	0.003
	2016	0.618	5.393	0.001
	2001-2016	0.482	4.518	0.001
Cash Crop EWF (m^3 USD^{-1})	**2001**	-0.009	0.184	0.411
	2006	0.04	0.653	0.24
	2011	0.139	1.501	0.066
	2016	-0.145	-0.914	0.187
	2001-2016	0.016	0.418	0.307

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Table 7. 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})			PWF$_g$(m^3 kg^{-1})			PWF(m^3 kg^{-1})		
	Current Study	Mekonnen and Hoekstra (2011)	Zhuo et al. (2016a)	Current Study	Mekonnen and Hoekstra (2011)	Zhuo et al. (2016a)	Current Study	Mekonnen and Hoekstra (2011)	Zhuo et al. (2016a)
	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	0.28	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	1.35
Soybean	0.53	0.25	0.11	2.34	2.55	2.02	2.87	2.80	2.13
Groundnuts	0.38	0.09	0.19	1.21	1.38	1.35	1.60	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	1.65

675 **Table 8. Comparison between economic value-based water footprint (EWF) in the current results and previous studies.**

Reference	Case	Year/Period	$EWF_{b,ir}$ m^3 USD^{-1}	$EWF_{g,ir}$ m^3 USD^{-1}	$EWF_{g,rf}$ m^3 USD^{-1}	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	27.64	3.81	7.24	7.33
	Spring Wheat in China		16.21	4.79	8.16	9.22

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