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Impacts of climate change on water footprint of spring wheat production: the case of an irrigation district in China

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Abstract

The potential impacts of climate change are expected to reshape the patterns of demand and supply of water for agriculture, therefore the assessment of the impacts of climate change on agricultural water consumption will be essential. The water footprint provides a new approach to the assessment of agricultural water consumption under climate change. This paper provides an analysis of the impacts of climate changes on the water footprint of spring wheat in Hetao Irrigation District, China during 1980-2009. Results indicate that: 1) crop evapotranspiration and irrigation water requirements of spring wheat presented a downtrend owing to the climate factors variation in the study period; 2) under the combined influence of increasing crop yield and decreasing crop evapotranspiration, the water footprint decreased during the study period, exhibiting a trend of 0.025 $m^3 kg^{-1} yr^{-1}$; 3) the total contribution rate of the climatic factors for the decline of water footprint of spring wheat during the study period was only –10.45%. These results suggest that the water footprint of a crop, to a large extent, is determined by agricultural management rather than by the regional agro-climate and its variation. Nevertheless, we should pay attention to the adaptation of effective strategies for minimizing the agricultural production risk caused by climate change.

Additional key words: agriculture water consumption; effective precipitation; ground water; Hetao Irrigation District; surface water; *Triticum aestivum*.

Resumen

Impactos del cambio climático sobre la huella hídrica de la producción de trigo de primavera: el caso de un distrito de riego en China

Es de esperar que los impactos potenciales del cambio climático redefinan los patrones de oferta y demanda de agua para la agricultura. Por ello es esencial la evaluación del impacto del cambio climático sobre este consumo y en esta evaluación el estudio de la huella hídrica ofrece nuevas alternativas. Este trabajo analiza los impactos del cambio climático sobre la huella hídrica de trigo de primavera en el Distrito de Riego Hetao, China, entre 1980 y 2009. Los resultados indican que: 1) la necesidad de agua de los cultivos y el requerimiento de agua de riego del trigo de primavera presentó una tendencia a la baja, debido a la variación de los factores climáticos en el período de estudio; 2) bajo la influencia combinada del aumento de rendimiento de los cultivos y la disminución en la evapotranspiración del cultivo, la huella hídrica disminuyó durante el período de estudio, tendiendo a 0,025 $m^3 kg^{-1}$ año^{-1}, 3) la tasa de contribución total de los factores climáticos en la disminución de la huella hídrica de trigo de primavera durante el período de estudio fue sólo –10,45%. Estos resultados sugieren que, en gran medida, la huella hídrica de un cultivo está más determinada por la gestión agrícola que por el agro-clima de la región y sus variaciones. Sin embargo, debemos prestar atención a la adaptación de estrategias eficaces para minimizar el riesgo provocado por el cambio climático en la producción agrícola.

Palabras clave adicionales: aguas subterráneas; aguas superficiales; consumo de agua en la agricultura; huella hídrica; distrito de riego Hetao; precipitación efectiva; *Triticum aestivum*.

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Abbreviations used: BWF (blue water footprint); ET_c (crop evapotranspiration); GWF (green water footprint); IWR (irrigation water requirements); WF (water footprint).

Introduction

Freshwater is a fundamental element in every aspect of human existence. It is essential for the economy, social order and life itself (Maeda *et al.*, 2011). However, water crisis has become a hot spot around the world since the gap between increased demands and limited water resources has increasingly been widened. Currently, roughly 70% of freshwater withdrawals are used for agricultural production (FAO, 2005; Xiong *et al.*, 2010; Fader *et al.*, 2011), particularly so in China where the proportion is more than 60% (MWR, 2010). Increasing competition for water resources, coupled with climate change may have significant influences on water availability for agricultural production. The potential impacts of climate change on the global hydrological cycle are expected to reshape the patterns of demand and supply of water for both irrigated and rain-fed agriculture across the world (Ohmura & Wild, 2002; FAO, 2011). Rising temperature will translate into increased crop evapotranspiration, variation of crop yield and water productivity (FAO, 2011). To adapt agricultural systems to the changing climate, it is important to know how climate change affects agricultural production and water use efficiency. Hence, the assessment of water resources utilization during the agricultural production process under climate change will contribute to improving agricultural water management practices to cope with climate change.

Water footprint (WF) provides a new approach for assessing water resources utilization in the agricultural production process (Hoekstra & Hung, 2002; Hoekstra *et al.*, 2011). The water footprint of a product is the volume of water used to produce the particular product, measured at the point of production. The water footprint of crop production is defined as the volume of freshwater both consumed and affected by pollution during the crop production process, and it has three components: 1) green water footprint (the volume of the precipitation consumed in crop production process); 2) blue water footprint (the volume of surface or groundwater consumed in crop production process); and 3) grey water footprint (the volume of freshwater that is required to assimilate the load of pollutants during the crop production process) (Chapagain & Hoekstra, 2011). Thus far, emphasis has been given to the blue water footprint of conventional agricultural water management. However, a growing number of authors highlight the importance of green water on guaranteeing food security by sustaining rain-fed crop production (Falkenmark & Rockström, 2004; CAWMA, 2007; Rockström *et al.*, 2009; Aldaya *et al.*, 2010). The water footprint is not only an indicator of water use that looks at both water consumption and pollution, but can also broaden water resources evaluation systems and provide water utilization information for decision-making (Ma *et al.*, 2005; Ercin *et al.*, 2011). Several studies have been focused on developing the concept of water footprint and quantifying the water footprint of a large variety of products from a consumption perspective at either global or national scales (Long *et al.*, 2005; Ma *et al.*, 2005; Chapagain & Hoekstra, 2007; Chapagain & Orr, 2009; Bulsink *et al.*, 2010; Liu & Yang, 2010; Mekonnen & Hoekstra, 2011). These studies have contributed to the development of the water footprint theory. Few of them, however, focus on the long time sequenced analysis of the water footprint for a crop at the irrigation district scale from the production perspective or take into account the impacts of regional climate variation. Meanwhile, earlier studies treated the countries as a whole, without considering the heterogeneity within the countries (Chapagain & Hoekstra, 2011; Hoekstra *et al.*, 2011; Montesinos *et al.*, 2011; Mekonnen & Hoekstra, 2011).

The WF can distinguish the green and blue water of crop water consumption, and may contribute to the assessment of agricultural water utilization, as it permits the comparison of crops from the perspective of water consumption type. It can also reflect the water productivity of crop production (Chapagain & Hoekstra, 2011). In view of the above properties of WF, the present paper evaluates the interannual variability of the water footprint for spring wheat (*Triticum aestivum*) production during 1980-2009, differentiating between the sources of water (green and blue) in the Hetao Irrigation District. Then, we assess the impacts of climate change on water footprint of spring wheat and to analyze the major influencing factors that caused the variation of water footprint for spring wheat production. The grey water footprint of a crop refers to the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. It is a theoretical value that is not truly consumed by the crop. Therefore, this paper only takes into account the total water consumption (green plus blue footprint) for crop production.

Material and methods

Study area

The Hetao Irrigation District is located in the middle of the Yellow River Basin in the west of Inner Mongo-

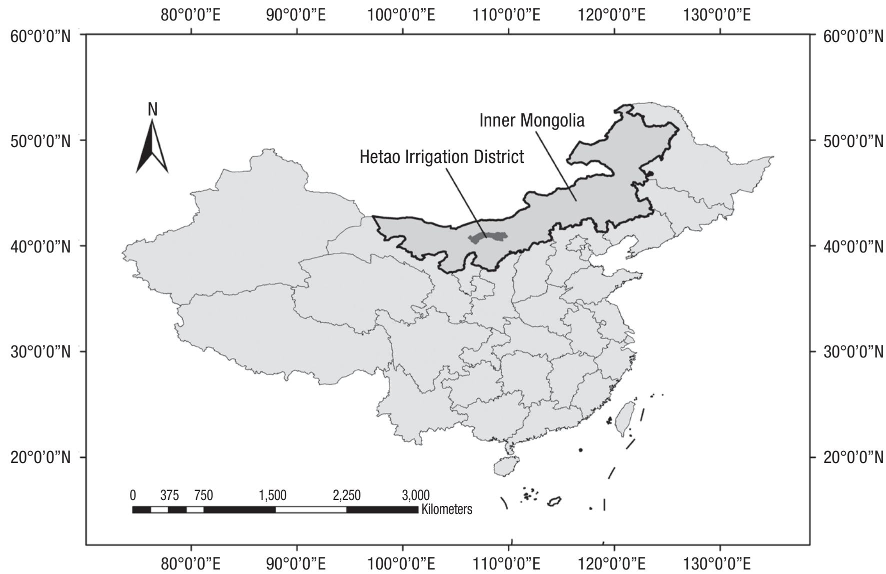

Figure 1. The location of Hetao Irrigation District.

lia, China (Fig. 1). Hetao Irrigation District has a continental monsoon climate, where weather is dry and hot in summer and severely cold with little snow in winter. The annual precipitation is 136.8-213.5 mm, annual evaporation is 1,993-2,373 mm and annual average temperature is 6-8°C. The major crops are spring wheat, maize (*Zea mays*) and sunflower (*Helianthus annuus*) (Bai *et al.*, 2010).

In the past years, the Hetao Irrigation District extracted about 5 × 10^9 m^3 water annually from the Yellow River. With the increasing pressure of water scarcity in northern China, the Hetao Irrigation District is allowed to divert about 4 × 10^9 m^3 as set by the government (Bai *et al.*, 2010). Although agricultural water use efficiency has increased substantially through improving water delivery systems and irrigation methods throughout the Hetao Irrigation District, it is difficult to compensate for the steady rise in irrigation water demand resulting from the expansion of the irrigated area. This situation could become even more severe under climate change. The Hetao Irrigation District is located in a semi-arid region that is impressionable to the potential impact of climate change (Tao *et al.*, 2003). In the future, crop evapotranspiration and water use efficiency of crop is expected being altered with climate change (Thomson *et al.*, 2006; Thomas, 2008; Guo *et al.*, 2010). In order to alleviate this contradiction, the Irrigation District needs to improve the agricultural water resources management level for saving water, and the prerequisite to achieve this goal is the rational evaluation of the water resources utilization during agricultural production process.

Data description

The data used in this study included climate data, agriculture statistical data and irrigation data. The climate data (1980-2009) was taken from the China Meteorological Data Sharing Service System (CMA, 2010), including monthly average maximum temperature, monthly average minimum temperature, relative humidity, precipitation, wind speed and sunshine hours.

The agricultural data, including crop yield, sowing area, soil type and agricultural inputs, was taken from the "Inner Mongolia statistical year-book", "China agricultural statistics data", etc. (MAC, 1980-2009; NBSC, 1980-2009).

The volume of water withdrawn from Yellow River for irrigation was supplied by Irrigation District authorities for the 1980-2009 hydrological year-book. The irrigation water volume allocated per area was then distributed proportionally among the crops according to their theoretical irrigation water requirements, which were calculated according to Allen *et al.* (1998).

Methods

The WF of crop production depends on the crop water consumption (including blue water and green water) over the crop growing period and the crop yield

(Hoekstra *et al.*, 2011). Interannual variability of climatic factors would cause the variation of crop evapotranspiration (ET_c), irrigation water requirements (IWR) (the amount of irrigation water required to compensate the evapotranspiration loss from a cropped field and it is the difference between the crop evapotranspiration and the effective precipitation during crop growing period) and crop yield, and it will exert an indirect impact on the WF of spring wheat. Therefore, this paper first evaluates the interannual variation of climatic factors in Hetao Irrigation District. Next, it analyzes the response of ET_c and IWR to climate change, before going on to assess their influences on the WF of spring wheat production.

Temporal variation of climatic factors

The Mann-Kendall (M-K) trend test (Mann, 1945; Kendall, 1948) is used to analyze the trends and abrupt changes of the climatic factors. The time series of climatic factors could be regarded as $x_1, x_2, \dots, x_n$. For each term, m_i is computed as the number of later terms in the series whose values exceed x_i. The test statistic is calculated as follows (Birsan *et al.*, 2005; Liang *et al.*, 2011):

$$d_k = \sum_{i=1}^{k} m_i \ \left(2 \le k \le n\right) \qquad [1]$$

The expected value $E(d_k)$ and variance of $Var(d_k)$ can be calculated as follows:

$$\begin{cases} E\left[d_k\right] = k\left(k-1\right)/4 \\ \mathrm{var}\left[d_k\right] = k\left(k-1\right)\left(2k+5\right)/72 \end{cases} \left(2 \le k \le n\right) \qquad [2]$$

The d_k was standardized as $u(d_k)$ as follows:

$$u(d_k) = \left(d_k - E\left[d_k\right]\right) \Big/ \sqrt{\mathrm{var}\left[d_k\right]} \qquad [3]$$

The null hypothesis of no trend in climatic variation will be rejected at a confidence level of α if the standard normal probability $\Pr ob(\left|z\right| < \left|u(d_k)\right|) > \alpha$ (Serrano *et al.*, 1999). Given that $u(d_1) = 0$, the terms of the $u(d_k)$ ($1 \le k \le n$) constitute the curve UF. A typical confidence level of 95% was used with climatic factors series.

Applying the method to the inverse series, we can obtain the series of $\bar{u}(d_k)$ as follows (Liang *et al.*, 2011):

$$\begin{cases} \bar{u}\left(d_k\right) = -u\left(d_{k'}\right) \\ k' = N + 1 - i \end{cases} (i, i' = 1, 2.....n) \qquad [4]$$

Given that $\bar{u}(d_1) = 0$, all $\bar{u}(d_k)$ will get a curve UB.

If UF exceeds the confidence line, it means that there is a significant upward or downward trend in the series. And if the intersection point of the UF and UB is between the two confidence lines, it signifies an abrupt climate change took place at that point (Hamed, 2008; Liang *et al.*, 2011).

WF calculating methodology

The green and blue water footprints of crop production were calculated following the calculation framework provided by Hoekstra *et al.* (2011):

$$WF_{green} = \frac{CWU_{green}}{Y} = 10 \quad \frac{ET_{green}}{Y} \qquad [5]$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} = 10 \quad \frac{ET_{blue}}{Y} \qquad [6]$$

where WF_{green} is the green water footprint (m^3 kg^{-1}), WF_{blue} the blue water footprint (m^3 kg^{-1}); CWU_{green} and CWU_{blue} are the green and blue water consumption (m^3 ha^{-1}); the factor 10 is meant to convert water depths (in mm) into water volumes per land surface (in m^3 ha^{-1}); ET_{green} and ET_{blue} represent the green and blue water evapotranspiration (mm); Y is the crop yield (kg ha^{-1}).

The ET_{green} is calculated as the minimum of total crop evapotranspiration and effective precipitation, the ET_{blue} is estimated as the difference between the total crop evapotranspiration and the total effective precipitation (Hoekstra *et al.*, 2011):

$$ET_{green} = \min(ET_c, P_e) \qquad [7]$$

$$ET_{blue} = \max(0, ET_c - P_e) \qquad [8]$$

where ET_c is crop evapotranspiration during the crop growing period (mm); P_e the effective precipitation over the crop growing period (mm).

The ET_c is calculated by using CROPWAT model as follows (Allen *et al.*, 1998; FAO, 2010):

$$ET_c = K_c \quad ET_0 \qquad [9]$$

where K_c is the crop coefficient; ET_0 the reference crop evapotranspiration (mm), calculated according to the FAO Penman-Monteith equation as follows (Allen *et al.*, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \times \frac{900}{T + 273} \times u_2 \times (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad [10]$$

where Δ is the slope of the vapor pressure curve (kPa°C^{-1}); R_n the net radiation at the crop surface (MJ m^{-2} d^{-1}); G the soil heat flux density (MJ m^{-2} d^{-1}); γ the psychrometric constant (kPa°C^{-1}); T the average air temperature (°C); u_2 the wind speed measured at 2 m height (m s^{-1}); e_s the saturation vapor pressure (kPa); e_a the actual vapor pressure (kPa).

Influence factors analysis of WF

As previously mentioned, the WF of a crop is mainly determined by the total water consumption (green plus blue water) during the crop growth period and the crop yield. In order to explore the impacts of climate change on the variation of WF for spring wheat, correlation and path coefficient analysis were used to identify the relationship between WF and the climate factors. Path analysis was first described by Wright (1921; 1934) as a mean of determining the influence of independent factors on dependent factors. There were five related climatic factors selected for the analysis: average temperature, relative humidity, wind speed, sunshine hours and precipitation.

Contribution rate of climatic factors for WF variation

The factor's contribution rate can reflect the share of dependent variable variation that was caused by the factor's variation. (Yang *et al.*, 2000). Through analyzing the contribution rate of climatic factors to the variation of the water footprint, we can quantify the impact of climatic factors on water footprint of spring wheat as follows (Yang *et al.*, 2000):

$$\delta_i = \frac{a_i \times \Delta F_i \times WF}{F_i \times \Delta WF} \quad [11]$$

where δ_i is the factor's contribution rate; a_i the elastic coefficient (a number that indicates the percentage change that will occur in one variable when another variable changes 1%); ΔF_i the variation of climatic factor i; ΔWF the variation of WF.

Results

Variation of major climatic factors

The climate change will exert direct influence on crop water consumption process and crop yield, and it will have an indirect effect on WF. Consequently, in order to assess the impact of climate variability on WF, six climatic factors were selected for the analysis: temperature, relative humidity, precipitation, wind speed, sunshine hours and reference crop evapotranspiration (ET_0).

The interannual variations of the six meteorological factors were significant from 1980 to 2009. The coefficient of variation (CV) of precipitation reached 0.259, and the highest annual precipitation was approximately 2.97 times that of the lowest value. The coefficient of variation of temperature (0.114) took second place, followed by wind speed (0.103), relative humidity (0.046), ET_0 (0.031) and sunshine hours (0.028) (Table 1).

The M-K test results on climatic factors throughout the 1980-2009 study period in Hetao Irrigation District showed that the temperature and precipitation experienced an upward trend between 1980 and 2009 for the M-K statistics values were greater than zero and the temperature upward trend reached a statistically significant level ($p < 0.05$) (Table 1), the growth rate of temperature was 0.07°C yr^{-1}. Meanwhile, temperature and precipitation abrupt changes occurred in 1993 and 1983, respectively. In contrast, the relative humidity, wind speed, sunshine hours and ET_0 showed a decreasing trend between 1980 and 2009, and wind speed reached a significant level ($p < 0.05$). The descent rate of wind speed was 0.02 (m s^{-1}) yr^{-1} (Fig. 2).

Table 1. Statistical analysis and M-K test of climatic factors

Statistical description	Temperature (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Sunshine hours (h)	Precipitation (mm)	ET_0 (mm)
Minimum	5.54	42.67	2.07	2,921.76	94.75	1,136.21
Maximum	8.72	51.42	3.02	3,234.48	281.80	1,280.09
Mean	7.20	47.11	2.40	3,092.72	173.12	1,217.15
SD	0.82	2.17	0.25	85.14	44.81	6.97
CV	0.114	0.046	0.103	0.028	0.259	0.031
M-K value	4.28	–0.79	–4.98	–1.46	0.86	–1.07
Abrupt change year	1993	2008	1993	1992	1983	1983

ET_0: reference crop evapotranspiration; SD: standard deviation; CV: coefficient of variation; M-K: Mann-Kendall test.

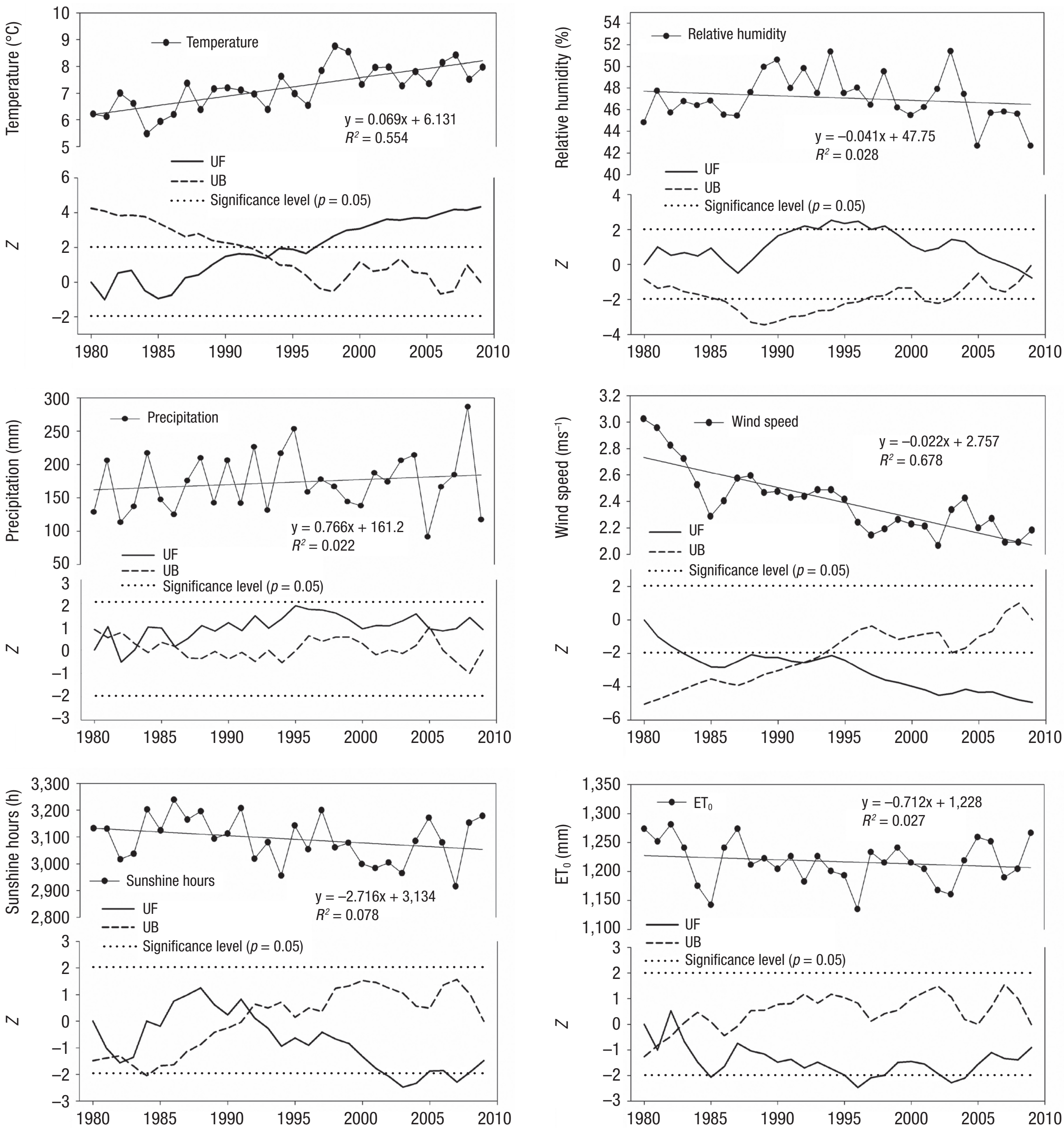

Figure 2. The temporal variation and M-K test of climatic factors during 1980-2009 in Hetao Irrigation District. UF: the term of the $u(d_k)$ (Eq. [3]); UB: the term of the $\overline{u}(d_k)$ (Eq. [4]).

The rising temperature and declining relative humidity would result in higher crop evapotranspiration (ET_c) and agricultural water consumption, while the decline in wind speed, sunshine hours combined with increase in precipitation will mitigate the adverse impacts of regional climate warming.

Impact of climate change on ET_c and IWR

Given these climatic variations in Hetao Irrigation District, the CROPWAT model was used to evaluate its impacts on ET_c and IWR of spring wheat. Fig. 3 shows the variation of ET_c and IWR of spring wheat between

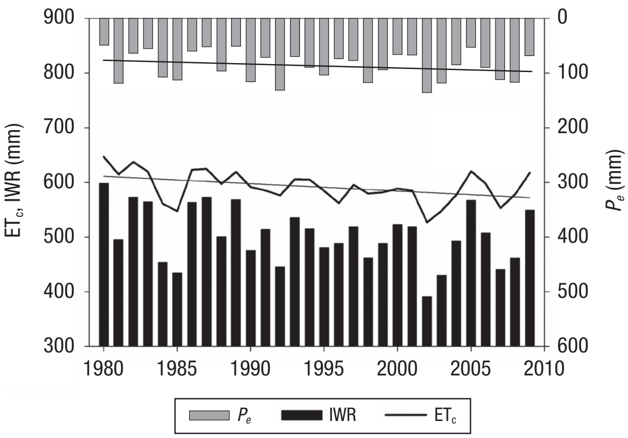

Figure 3. Interannual variability of crop evapotranspiration (ET_c), effective precipitation (P_e) and irrigation water requirements (IWR) of spring wheat.

1980 and 2009. Both presented a downtrend owing to the climate change in the study period, and the linear declining rates were 1.34 mm yr^{-1} and 1.95 mm yr^{-1}, respectively. The IWR showed greater fluctuation due to the obvious variation in precipitation of each year. In addition, under the combined influences of decreasing ET_c and increasing precipitation, the decrease rate of IWR was higher than ETc's. In order to further analyze the influence of the above climatic factor on ET_c of spring wheat, correlation analysis was used to identify the relationship between ET_c and its impact factors. The results showed that temperature (0.185*), wind speed (0.614**) and sunshine hours (0.338) were positively correlated with ET_c, the temperature and wind speed reached a significant level ($p < 0.05$ or $p < 0.01$), while relative humidity (–0.349) and precipitation (–0.433*) were negatively correlated with ET_c. Precipitation reached a significant level of ($p < 0.05$) (Table 2). Hence, the interannual variability of ET_c of spring wheat in Hetao Irrigation District was probably mainly caused by changes in temperature, wind speed and precipitation in each year.

The variation of WF

Fig. 4 presents the interannual variability of WF of spring wheat between 1980 and 2009. Under the combined influence of increasing crop yield and decreasing ET_c, the WF decreased during the study period, exhibiting a trend of 0.025 m^3 kg^{-1} yr^{-1}. The average annual water footprint (green plus blue water footprint) during the study period was 1.24 m^3 kg^{-1}. From the perspective of its components, the share of the blue water footprint in total water consumption is relatively high (more than 85%), while for the share of green water footprint it is relatively small (< 15.00%). Therefore, the production of spring wheat in the Hetao Irrigation District mainly relies on blue water resources (irrigation water).

Fig. 5(a) shows the interannual variability and departure percentage of green water footprint (GWF) of spring wheat. The GWF exhibited a fluctuating and decreasing trend during the study period, with a trend of 0.001 m^3 kg^{-1} yr^{-1}. The GWF experienced a higher value period from 1980 to 1985. Since 1986, however, the GWF entered into a lower value stage. The GWF

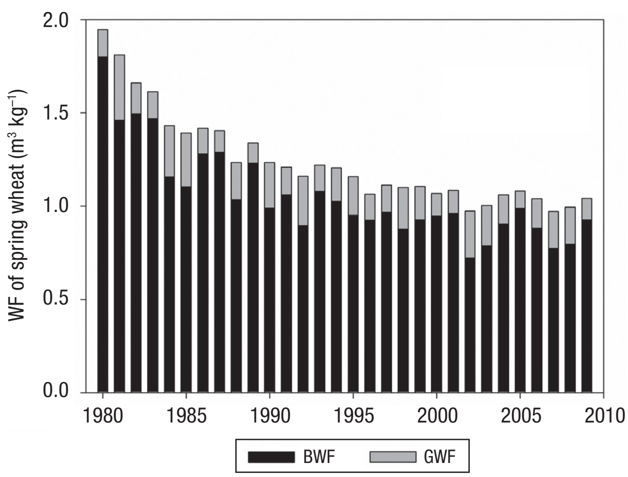

Figure 4. Interannual variability of water footprint of spring wheat. GWF: green water footprint; BWF: blue water footprint.

Table 2. The Pearson correlation among water footprint (WF), yield, evapotranspiration (ET_c) of spring wheat and its impact factor

	Temperature (°C)	Relative humidity (%)	Wind speed (m s^{-1})	Sunshine hours (h)	Precipitation (mm)
WF	0.646**	–0.092	0.909**	0.253	–0.244
Yield	0.727**	–0.068	–0.857**	0.229	0.149
ET_c	0.185*	–0.349	0.614**	0.338	–0.433*

WF: water footprint; ET_c: crop evapotranspiration. * significant at $p < 0.05$, ** significant at $p < 0.01$.

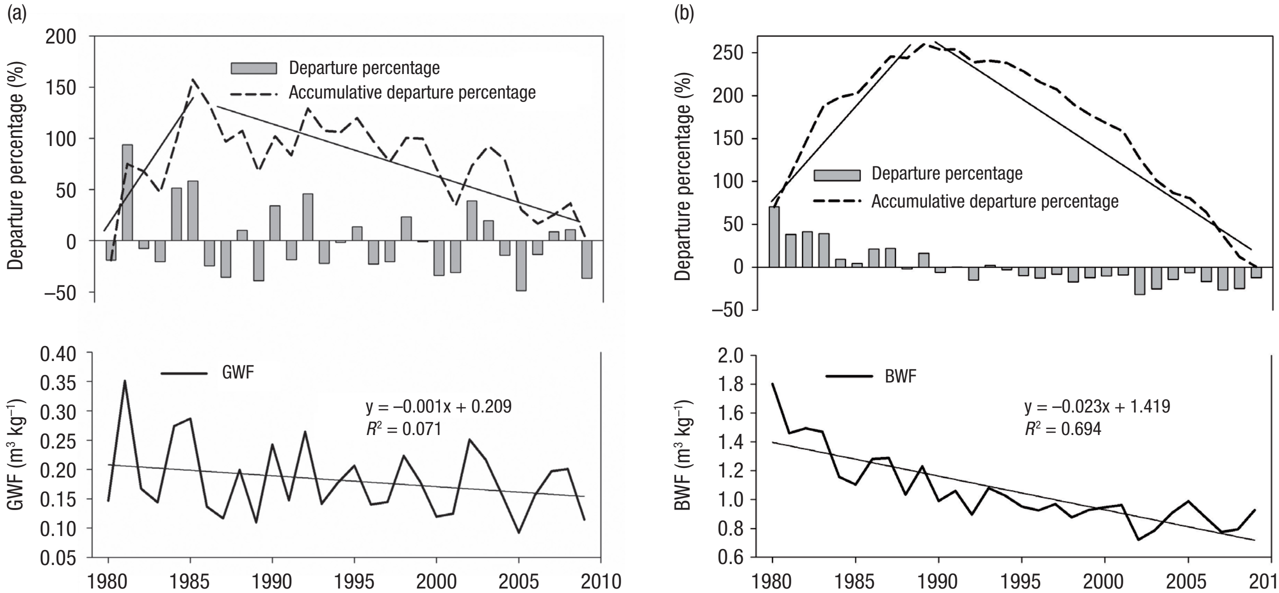

Figure 5. Interannual variability of green water footprint (GWF) (a) and blue water footprint (BWF) (b) of spring wheat.

is mainly affected by effective precipitation during the spring wheat growing period and crop yield. According to the above analysis, the precipitation during the spring wheat growing period presented non-significant upward trend during the study period, while the yield showed a significant upward trend. Under the combined influence of the two factors, the GWF presented a downward trend from 1980 to 2009.

Fig. 5(b) presents the interannual variability of blue water footprint (BWF). BWF decreased during the study period with a trend of 0.023 $m^3\,kg^{-1}\,yr^{-1}$. The departure percentage of BWF showed that BWF experienced higher values from 1980 to 1989, and showed lower values since 1990. The BWF is mainly determined by the volume of blue water consumption (irrigation water from surface or ground water) during the spring wheat growing period and crop yield. The irrigation water requirements displayed a declining trend in the study period. Meanwhile, the spring wheat yield presented an obvious increasing trend owing to the improvement of agricultural productivity. Under the integrated effects of these factors, the BWF displayed a relatively significant downtrend.

Influence of climatic factors variation on WF of spring wheat

The correlation analysis among WF of spring wheat and climatic factors revealed that temperature, wind speed and sunshine hours were positively correlated with WF, and the temperature and wind speed reached a statistically significant level ($p < 0.01$). In contrast, a negative correlation was observed between WF and relative humidity and precipitation (Table 2). The results of the path coefficient analysis of WF and the climatic factors showed that the total influence of the five climatic factors on WF were, in sequence, wind speed, temperature, precipitation, sunshine hours, and relative humidity (Table 3).

We can obtain the elasticity coefficient of the five climatic factors by applying multiple linear regressions and generalized least square method (Table 4). By significance test, only the temperature and wind speed reached the significant level ($p < 0.05$), and by using Eq. [11], the contribution rate of the climatic factors can be calculated (Table 5). The results showed that the contribution rate of climatic factors were rela-

Table 3. The path coefficient among WF and its impact factors

	Temperature (°C)	Relative humidity (%)	Wind speed ($m\,s^{-1}$)	Sunshine hours (h)	Precipitation (mm)
Path coefficient	0.131	–0.014	0.151	0.082	–0.074
Total influence	0.196	–0.073	0.339	0.094	–0.131

Table 4. The elasticity coefficient of the climatic factors

Climatic factors	Elasticity coefficient	Standard error	Probability
Temperature	0.215	0.084	0.019
Relative humidity	–0.050	0.243	0.839
Wind speed	0.377	0.138	0.049
Sunshine hours	0.574	0.324	0.092
Precipitation	–0.053	0.030	0.098

tively small. Total contribution rate of the climatic factors was –10.45%, while temperature was 9.88%, and wind speed was –20.33%. It signified that with the increase of temperature, the WF of spring wheat has gained 9.88%, while the WF has fallen 20.33% due to the decrease of wind speed in the study period.

Discussion

Climate change has been largely accepted as a real, pressing and truly global problem. The main arguments concern how much climate change there will be, what impacts will ensue and how best to adapt to them (FAO, 2011). The anticipated impacts of climate change would pose an additional stress on agricultural production systems under pressure to meet the food needs of a rapidly growing world. The assessment of the impacts of climate change on water and agriculture will be essential for putting viable and effective adaptations to guarantee the food security of the world in the context of climate change (FAO, 2011). In assessing the impacts of climate change on agriculture production and agricultural water management, it is clear that the volume and the type of agricultural water consumption (green water and blue water) will be a critical factor. Water footprint provides a new approach for assessing water resources utilization in the agriculture production process (Hoekstra & Hung, 2002; Chapagain & Hoekstra, 2011).

Table 5. The contribution rate of climatic factors for WF variation

Climatic factors	Elasticity coefficient	Factors variation ratio (%)	Contribution rate (%)
Temperature	0.215	23.57	9.88
Wind speed	0.377	–27.72	–20.33
Total contribution rate			–10.45

The results of the above case study showed that the multi-year average water footprint of spring wheat in Hetao Irrigation District was 1.24 m^3 kg^{-1}. A comparison of our estimates with previous studies shows that most of the former studies focus on consumption perspective at either global or national scales (Chapagain & Orr, 2009; Bulsink *et al.*, 2010). The estimate of the total water footprint related to wheat production by Mekonnen & Hoekstra (2010) is 1.37 m^3 kg^{-1} of Inner Mongolia, China, which is 10.48% higher than our estimate in Hetao Irrigation District. The differences in the results of the two studies can be due to a variety of causes, including: crop species (spring wheat or winter wheat), spatial resolution, crop grown periods, crop parameters, soil and climate conditions (Mekonnen & Hoekstra, 2011). It could also signify that the crop water productivity of Hetao Irrigation District is higher than Inner Mongolia, in average.

From the perspective of its components, the BWF accounted for a larger proportion of the total WF (more than 85%). The grown of spring wheat in Hetao Irrigation District mainly depends on blue water (irrigation water). Green water generally has a lower opportunity cost than blue water (Aldaya *et al.*, 2010; Hoekstra *et al.*, 2011). In contrast to the green water, blue water resources are generally scarcer and the use of blue water is restricted by its scarcity, high opportunity cost and large influence on environment. Often, this becomes the limiting factor to the development of the socio-economy in water scarce regions. Therefore, determining how to reduce blue water consumption in agricultural production, and how to divert the blue water to other departments has become the target of countries and regions around the world (Aldaya *et al.*, 2010). Therefore, better use of rain wherever possible, that means increasing yields per drop of rainwater, will reduce the demand for blue water in agricultural production process (Chapagain & Hoekstra, 2011). Meanwhile, water resources availability will be altered by climate change, such as changing rainfall patterns and increasing rates of evapotranspiration. Consequently, the rain-fed agriculture will become more precarious with climate changes, so it is sensible to establish a comprehensive utilization system for the two water resources to cope with the adverse impacts of climate change.

The WF of crop production depends on two factors: the total water consumption (green and blue water) and the crop yield. The climatic change will not only affect crop water consumption but crop yield as well. For instance, rising temperatures will translate into increased crop evapotranspiration, while producing a reduction in crop yield and agricultural productivity where temperature constrains crop development (FAO, 2011). The results of the above case study showed that the climatic factors were not the dominate factors that caused the decline of spring wheat WF during the study period, for the total contribution rate of the climatic factors was only –10.45%. This suggests that the water footprint of crop production, to a large extent, is determined by agricultural management rather than by the agro-climate and its variation. Some previous studies have shown that the crop production will depend not only on climate change effects, but also on further improvements in technology and crop management (Olesen & Bindi, 2002; Jones & Thornton, 2003). Alexandrov & Hoogenboom (2000) suggested that the sowing dates of spring crops could shift under the climate change scenarios in order to reduce yield losses caused by an increase in temperature. Thus, the selection of an earlier sowing date for maize will probably be the appropriate response to offset the negative effect of a potential increase in temperature (Yano *et al.*, 2007). Xiong *et al.* (2010) also indicated that the irrigation water requirements was influenced not only by the climate variation but the management practices as well, such as crop sowing date, growth period, cultivation methods, etc. (Nangia *et al.*, 2008).

Although the WF theory provides an effective framework for assessing agricultural water consumption during the crop production process, there are some uncertainties that should be of concern in the quantification of the green and blue water footprints of a crop. The study suffers limitations in terms of data availability and quality. The quality of data used determines the accuracy of the calculation output. For instance, owing to the absence of planting and harvesting time in each year, the planting and harvesting dates of spring wheat used in the study were deemed the same during 1980-2009, and it was not according with the realistic condition. Furthermore, in the process of quantifying blue water footprint, the irrigation is assumed to be sufficient to cover the irrigation water requirements. But in reality, the crop may suffer water stress, particularly in those regions where water is scarce (Mekonnen & Hoekstra, 2011). Also, the former studies quantified the WF of a crop through computing the crop evapotranspiration by using CROPWAT model. This quantization method does not take into account the irrigation water losses during the transmission and distribution process from the water sources to the farmland. Therefore, it could not reflect the actual water consumption and water use efficiency at the regional scale. Consequently, it would bring some uncertainties to the assessment of agricultural water use. In addition, although product water footprinting promises to be a useful driver of sustainable consumption and production, with potential to encourage global-scale change with respect to freshwater resource consumption, other approaches to environmental protection and management will also be required (Ridoutt & Pfister, 2010). Therefore, future studies are worthy to be carried out to improve the WF calculation framework.

As conclusions, the climatic factors were not the dominate factors that cause the decrease of WF of spring wheat in the Hetao Irrigation District, China. The results suggested that the water footprint of a crop mainly depends on agricultural production level rather than the local climate condition and its variation. However, effective measures should be taken to mitigate the adverse effects caused by climate change in the long run. Significant productivity increases can be expected in both crop yield and water use efficiency by better management of all agricultural inputs and farming practices.

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References

Aldaya MM, Allan JA, Hoekstra AY, 2010. Strategic importance of green water in international crop trade. Ecol Econ 69: 887-894.

Alexandrov VA, Hoogenboom G, 2000. The impact of climate variability and change on crop yield in Bulgaria. Agr Forest Meteorol 104: 315-327.

Allen RG, Pereira LS, Raes D, Smith M, 1998. Crop evapotranspiration: guidelines for computing crop water requirements. FAO Drain Irrig Paper 56, Food and Agriculture Organization, Rome.

Bai GS, Zhang R, Geng GJ, Ren ZH, Zhang PQ, Shi JG, 2010. Integrating agricultural water-saving technologies in Hetao Irrigation District. Bulletin of Soil and Water Conservation 31(1): 149-154. [In Chinese].

Birsan MV, Molnar P, Burlamdo P, Pfaundler M, 2005. Stream flow trends in Switzerland. J Hydrol 314: 312-329.

Bulsink F, Hoekstra AY, Booij MJ, 2010. The water footprint of Indonesian provinces related to the consumption of crop products. Hydrol Earth Syst Sc 14(1): 119-128.

CAWMA, 2007. Water for food, water for life: a comprehensive assessment of water management in agriculture. Earthscan, London.

Chapagain AK, Hoekstra AY, 2007. The water footprint of coffee and tea consumption in the Netherlands. Ecol Econ 64: 109-118.

Chapagain AK, Orr S, 2009. An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes. J Environ Manage 90: 1219-1228.

Chapagain AK, Hoekstra AY, 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol Econ 70: 749-758.

CMA, 2010. China Meteorological Data Sharing Service System. China Meteorological Administration, Beijing. Available in http://cdc.cma.gov.cn/ [Accessed 06 June 2011].

Ercin AE, Aldaya MM, Hoekstra AY, 2011. Corporate water footprint accounting and impact assessment: The case of the water footprint of a sugar-containing carbonated beverage. Water Resour Manage 25(2): 721-741.

Fader M, Gerten D, Thammer M, Heinke J, Lotze-Campen H, Lucht W, Cramer W, 2011. Internal and external green-blue agricultural water footprints of nations, and related water and land savings through trade. Hydrol Earth Syst Sc 15: 1641-1660.

Falkenmark M, Rockström J, 2004. Balancing water for humans and nature: the new approach in ecohydrology. Earthscan, London.

FAO, 2005. AQUASTAT Information System on Water and Agriculture: Online database. Food and Agriculture Organization of the United Nations, Land and Water Development Division, Rome.

FAO, 2010. CROPWAT Model. Food and Agriculture Organization of the United Nations, Land and Water Development Division, Italy. Available from:www.fao.org/nr/water/inforesdatabasescropwat.html [Accessed 09 June 2011].

FAO, 2011.Climate change, water and food security. Food and Agriculture Organization of the United Nations, Land and Water Development Division, Rome.

Guo RP, Lin ZH, Mo XG, Yang CL, 2010. Responses of crop yield and water use efficiency to climate change in the North China Plain. Agr Water Manage 97: 1185-1194.

Hamed KH, 2008. Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. J Hydrol 349: 350-363.

Hoekstra AY, Hung PQ, 2002. Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. Value of Water Research Report Series No. 11, UNESCO-IHE, Delft, The Netherlands.

Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM, 2011. The Water Footprint Assessment Manual. Earthscan, London.

Jones PG, Thornton PK, 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environ Change 13: 51-59.

Kendall MG, 1948. Rank correlation methods. Hafner, NY.

Liang LQ, Li LJ, Liu Q, 2011. Precipitation variability in Northeast China from 1961 to 2008. J Hydrol 404: 67-76.

Liu J, Yang H, 2010. Spatially explicit assessment of global consumptive water uses in cropland: green and blue water. J Hydrol 384: 187-197.

Long AH, Xu ZM, Zhang ZQ, Su ZY, 2005. Primary estimation of water footprint of Gansu Province in 2000. Resour Sci 27: 123-129. [In Chinese].

Ma J, Wang DX, Lai HL, Wang Y, 2005. Water footprint-An application in water resources research. Resour Sci 27: 96-100. [In Chinese].

MAC, 1980-2009. Chinese agricultural statistics statistical data. Ministry of Agriculture of the People's Republic of China. Chinese Agricultural Press, Beijing.

Maeda EE, Pellikka K, Clark BJ, Siljander M, 2011. Prospective changes in irrigation water requirements caused by agricultural expansion and climate changes in the eastern arc mountains of Kenya. J Environ Manage 92: 982-993.

Mann HB, 1945. Non-parametric test against trend. Econometrika 13: 245-259.

Mekonnen MM, Hoekstra AY, 2010. The green, blue and grey water footprint of crops and derived crop products. Value of Water Research Report Series No. 47, UNESCO-IHE, Delft, The Netherlands. Available in http://www.waterfootprint.org/Reports/ Report47WaterFootprint-CropsVol1.pdf.

Mekonnen MM, Hoekstra AY, 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol Earth Syst Sc 15: 1577-1600.

Montesinos P, Camacho E, Campos B, Rodríguez-Díaz JA, 2011. Analysis of virtual irrigationwater. Application to water resources management in a mediterranean river basin. Water Resour Manage 25: 1635-1651.

MWR, 2010. China water resources bulletin. Ministry of Water Resources of the People's Republic of China, Water Resources and Electricity Press, Beijing.

Nangia V, Turral H, Molden D, 2008. Increasing water productivity with improved N fertilizer management. Irrig Drainage Syst 22: 193-207.

NBSC, 1980-2009. Inner Mongolia statistical year-book. National Bureau of Statistics of China, China Statistical Press, Beijing.

Ohmura A, Wild M, 2002. Climate change: is the hydrological cycle accelerating? Science 298: 1345-1346.

Olesen JE, Bindi M, 2002. Consequences of climate change for European agricultural productivity, land use and policy. Eur J Agron 16: 239-262.

Ridoutt BG, Pfister S, 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Global Environ Change 20: 113-120.

Rockström J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D, 2009. Future water availability for global food production: the potential of green water for increasing resilience to global change. Water Resour Res 45: W00A12. doi:10.1029/2007WR006767.

Serrano A, Mateos VL, Garcia JA, 1999. Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921–1995. Phys Chem Earth 24: 85-90.

Tao FL, Yokozawa M, Hayashi Y, Erda L, 2003. Future climate change, the agricultural water cycle, and agricultural production in China. Agr Ecosyst Environ 95: 203-215.

Thomas A, 2008. Agriculture irrigation demand under present and future climate scenarios in China. Global Planet Change 60(3-4): 306-326.

Thomson AM, Izaurralde RC, Rosenberg NJ, He XX, 2006. Climate change impacts on agriculture and soil carbon sequestration potential in the Huang-Hai Plain of China. Agr Ecosyst Environ 114: 195-209.

Wright S, 1921. Correlation and causation. J Agric Res 20: 557-585.

Wright S, 1934. The method of path coefficients. Ann Math Stat 5: 161-215.

Xiong W, Holman I, Lin ED, Conway D, Jiang JH, Xu YL, Li Y, 2010. Climate change, water availability and future cereal production in China. Agr Ecosyst Environ 135: 58–69.

Yang Q, Zhu RX, Zhang J, Han WT, 2000. Mechanization profit portion estimation in plant products industry in Shaanxi Province. Transactions of the CSAE 16(6): 64-67. [In Chinese].

Yano T, Aydin M, Haraguchi T, 2007. Impact of climate change on irrigation demand and crop growth in a mediterranean environment of Turkey. Sensors 7: 2297-2315.