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Spatial-temporal assessment of water footprint, water scarcity and crop water productivity in a major crop production region

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ABSTRACT

Irrigated agriculture has had an enormous influence on food security, water security and human well-being. Water footprint (how much water is used), water scarcity (how scarce water is), and crop water productivity (how much productivity irrigation adds) are important indicators for evaluating sustainability in irrigated agriculture. Yet these interrelated indicators have not been studied simultaneously at the county level – the basic administrative unit of agricultural planning and water management in countries such as China, India and Japan. To fill this knowledge gap, we performed a demonstration in China's major crop production region, the North China Plain (NCP)'s 207 counties from 1986 to 2010. The results show that the irrigated agriculture's annual water footprint in the North China Plain increased from 53 billion m^3 in 1986 to 78 billion m^3 in 2010. All counties faced water scarcity during 1986-2010 even as the average crop water productivity increased from 0.90 $kg\,m^{-3}$ to 1.94 $kg\,m^{-3}$. There are 173 NCP counties suffering severe water scarcity but still producing significant crop yield with a high water footprint, a red flag of unsustainable irrigated agriculture. This study has implications for revealing potential unsustainable conditions in irrigated agriculture worldwide.

1. Introduction

Global challenges involving food and water play significant roles in sustainability and human well-being worldwide. The Earth's freshwater resources have been facing tremendous pressure due to increasing consumptive use and water pollution (Steffen et al., 2015; Mekonnen and Hoekstra, 2016). For example, global water withdrawal increased 630 percent during 1900–2010 (Food and Agriculture Organization of the United Nations, 2018). Global food production also faces great challenges since by 2050, 9 billion people would need to be fed (Godfray et al., 2010).

Irrigated agriculture has important implications for both water security and food security. It accounts for more than 70% of the total water use, and more than 90% of total consumptive water use worldwide (consumptive water use is water removed from available supplies without return to a water resource system) (Döll, 2009; Food and Agriculture Organization of the United Nations, 2018). Forty percent of global agricultural production requires irrigation (Viala, 2008).

Much effort has been made to improve irrigated agriculture's performance on water consumption and crop yields for more sustainable development. Many public policies have been applied and billions of dollars spent to save water in irrigated agriculture (Ward and Pulido-Velazquez, 2008). The water footprint, water scarcity, and crop water productivity are used as indicators to assess water and food sustainability. A product's water footprint (WF) is the total volume of freshwater consumed to produce the product (Liu et al., 2009; Mekonnen and Hoekstra, 2011). WF includes not only direct water consumption of products, but also indirect water consumption – water indirectly consumed and water polluted throughout the production chain. Water scarcity shows a shortage of renewable fresh water compared to water demand (Raskin et al., 1996; Damkjaer and Taylor, 2017). We measure agricultural water use

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against renewable agricultural water resources to represent the extent of water scarcity in agriculture (Raskin et al., 1996; Damkjaer and Taylor, 2017). Crop water productivity refers to the amount of crop produced per unit of water used. China is challenged to increase crop water productivity to relieve pressures that agriculture puts on water resources while increasing crop production (Wang et al., 2014). Evaluating water footprints presents a comprehensive picture of the relationship between water consumption and human appropriation, because a water footprint includes both direct water consumption of products and water indirectly consumed and polluted during production. Assessing the impacts of water scarcity helps pinpoint vulnerable hotspots for solving the problem. Exploring crop water productivity can facilitate understanding the trade-offs between food production and water consumption. Holistically, understanding all three variables can illuminate pathways to alleviate conflicts between water security and food security.

Many studies have focused on water footprint, water scarcity and crop water productivity separately (Hoekstra and Mekonnen 2011, 2012; Jaramillo and Destouni, 2015; Zhao et al., 2015; Ashraf Vaghefi et al., 2017; Sun et al., 2017). Hoekstra and Mekonnen (2012) has quantified and mapped the water footprint of humanity with high spatial resolution and found that agricultural production accounted for almost 92% of global WF footprint during 1996–2005 (Hoekstra and Mekonnen, 2012). Jaramillo et al. (2015) studied the global effects of flow regulation and irrigation on global freshwater conditions and revealed that the two can raise the global water footprint of humanity by approximately 18% (Jaramillo and Destouni, 2015). Hoekstra and Mekonnen (2011) defined the blue water scarcity index as the ratio of blue water footprint to blue water availability, and applied this index in the world's major river basins (Hoekstra and Mekonnen, 2011). They found that the blue water scarcity level in 55% of the basins studied exceeded 100% at least one month of the year, meaning the blue water footprint surpassed available blue water in these study basins. Zhao et al. (2015) used the water scarcity index to investigate impacts of interprovincial virtual water flow on trading provinces' water scarcity, and found the virtual water flow could exacerbate trading provinces' water scarcity level (Zhao et al., 2015). Ashraf Vaghefi et al. (2017) assessed the crop water productivity of irrigated maize and wheat in Karheh River Basin by using a hydrological model and a river basin water allocation model (Ashraf Vaghefi et al., 2017). Their results indicated a close linear relationship between crop water productivity and yield. Sun et al. (2017) explored crop water productivity of wheat in the Hetao irrigation district at the field scale and analyzed the impacts of agricultural and climatic factors on crop water productivity (Sun et al., 2017). Their results showed that crop water productivity was highly sensitive to relative humidity, wind speed, and irrigation efficiency, while less sensitive to sunshine hours and the amount of fertilizers used.

To our knowledge, water footprint, water scarcity, and crop water productivity have not been assessed simultaneously at the county level in large plains over a temporal scale. Such information is urgently needed since the global irrigated agricultural area has nearly tripled from 1900 to 2005 amid growing population, water crisis and food shortage. Assessing them together can show a more comprehensive interrelationship among food production, water consumption, and water scarcity. This will help to construct targeted policies to achieve both food security and water security in irrigated agriculture. Different from most water footprint studies at coarse spatial scales (e.g., global and national scales) or focused on geographic units (e.g., 5' × 5′ or 30' × 30′ grid), a study at the county level helps to better understand and manage water conservation and food production because much of agricultural planning and water management (e.g., sown area, planned total crop yield, and permits of water use) is done at the county level in countries such as China, India, and Japan.

To fill this knowledge gap, we chose the North China Plain (NCP), with 207 counties, as a demonstration for integrated assessment. The NCP is the national agricultural base and main grain production area in China. The region includes the plain of Beijing, Tianjin City, Hebei Province, and part of Henan and Shandong provinces with 133 million people (Zhang et al., 2012). Approximately 80% of the seeded areas of all crops are grain areas, 96% of which are planted with winter wheat and summer maize (Wang et al., 2001). From 1986 to 2010, the total wheat production and maize production in the NCP had increased from 1.58 and 1.07 to 2.49 and 2.97 million tons, respectively. While the NCP needs water for agriculture, the available freshwater per capita annually in the plain – 302 m^3 per year (Zhang et al., 2011) – is less than 1/24 of the global average. This is far below the international standard of freshwater resource shortage with the 1000 m^3 threshold (Kang et al., 2013). Using such limited water resources to support large amounts of agricultural production and socioeconomic development is a great challenge, implicating significant impacts on national food security, water security, and sustainable development. Many policies and technology investments have been applied in the NCP to solve the water crisis and ensure sustainable water use for food production, but the outcome has not been assessed comprehensively. Exploring this problem in the NCP can have implications for not only China, but also other irrigated areas worldwide.

The aim of this study was to assess the water footprint, water scarcity and crop water productivity of irrigated agriculture at the county level in the NCP from 1986 to 2010. We calculated the blue, green, and grey water footprint to illustrate the dynamics of total water footprint (WF_{total}) in the whole NCP; applied the water scarcity index to study the impacts of water consumption from irrigated agriculture on water scarcity in each county; and measured the grain yield per unit water use to represent crop water productivity (Mekonnen and Hoekstra, 2011).

2. Materials and methods

2.1. Data sources

We compiled a set of data for our analyses, including agrometeorological data, basic agricultural data, and geographic information system (GIS) data. We obtained the agrometeorological data from the Meteorological Data Sharing Service System of National Meteorological Information Center of China. These data covered 69 meteorological stations in Beijing, Tianjin, Hebei Province, Shandong Province, and Henan Province and included average air temperature, maximum air temperature, minimum air temperature, hours of sunshine, and daily precipitation data from 1986 to 2010. These factors were used to calculate the reference evapotranspiration (ET_0) based on Penman-Monteith equation (Xu et al., 2017). The ET_0 was used for calculating water footprint. We also used data on the crop growth periods, estimation of accumulated temperature, and solar radiation of winter wheat and summer maize from the cited literature, to define crop water production function in different areas. We obtained basic county-level agricultural production data – the cultivated area, nitrogen use, amount of production of winter wheat and summer maize – from the Agricultural Information Institute of Chinese Academy of Agricultural Sciences, to help calculate effective rainfall and grey water footprint, and to explore the relationship between crop production and water footprint. The empirically measured data of ETc (crop evapotranspiration) were derived from Luancheng Agro-Eco-Experimental Station of the Chinese Academy of Sciences in

Shijiazhuang City, Hebei Province. We also acquired the digitized soil organic matter map data (at a scale of 1:14,000,000) in 2005 from the Data Center for Resources and Environmental Sciences of Chinese Academy of Sciences, to help define crop water functions in different areas. Furthermore, we received GIS shape files for provinces, counties, main cities, and the Yellow River. Our unit of analysis was the county. For agrometeorological data that were not at the county level, we used the ordinary Kriging method to interpolate data at agrometeorological stations to counties. Specifically, we converted vector data of stations into raster data and then calculated the sum value by zonal statistics for each county in ArcGIS (version 10.1 ESRI). Crop Water Production Function (CWPF) is the mathematical expression that describes the relationship between water use and crop production for a certain kind of crop. The function is mainly influenced by sunshine and heat factors such as photo-synthetically active radiation and effective accumulated temperature, and agricultural production factors such as soil organic matter, crop types and varieties (see details in Supplementary Information).

2.2. WF assessment

We assessed the WF for the entire grain production chain, which included both the consumptive water usage for crop growth (WF_{cons}) and the fresh water needed to dilute associated pollutants (WF_{grey}). According to the sources of water, WF_{cons} were further divided into WF_{blue} (the volume of surface water, shallow and deep groundwater used for irrigation) and WF_{green} (the volume of rainwater used for growing crops). More detailed procedures for the WF assessment methods (including all calculation equations) can be found in Supplementary Information.

2.2.1. WF_{cons}

WF_{cons} of crop production is the total actual consumption of water within its whole production chain. Often, it is difficult to directly measure WF_{cons}, thus the indirect water requirement method is used. The crop water requirement is assumed to be the needed water via crop evapotranspiration under optimal conditions, which is calculated by multiplying the reference ETc with a crop coefficient. Because actual crops are not always grown under optimal conditions, actual evapotranspiration should be less than optimal crop evapotranspiration and thus a water stress coefficient is introduced. The main factors that affected crop evapotranspiration include precipitation, air temperature, pressure, sunshine hours, wind speed, crop type, soil condition, and planted time. The calculation functions are given below (Hoekstra et al., 2011).

$$WF_{cons} = \frac{1000 \times ET_0 \times A}{Y} \tag{1}$$

$$ET_{\boldsymbol{c}} = K_c \times ET_0 \tag{2}$$

$$ET_0 = \frac{0.408\delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\delta + \gamma(1 + 0.34U_2)} \tag{3}$$

Where ET_a (mm) is the actual crop evapotranspiration; A(km^2) is the total planation area; Y (kg) is the total crop yield; K_c is crop coefficient comparing to reference crop evapotranspiration; ET_0 (mm) is reference crop evapotranspiration; R_n (MJ m^{-2} d^{-1}) is net radiation on surface of crop; G (MJ m^{-2} d^{-1}) is soil heat flux; T (°C) is average air temperature; U_2 (m s^{-1}) is wind speed at 2 m above ground; e_s (kPa) is saturation vapor pressure; e_a (kPa) is measured vapor pressure; δ (kPa $°C^{-1}$) is the slope of the curve between saturation vapor pressure and temperature; and γ (kPa $°C^{-1}$) is hygrometer constant.

For our proposed water consumption method, the actual crop evapotranspiration in Eq. (1) was calculated from the crop water production function (CWPF) shown below.

$$y = aET_a^2 + bET_a + c \tag{4}$$

$$ET_a = min\left(-\frac{b}{2a} \pm \sqrt{\frac{y}{a} + \frac{b^2}{4a^2} - \frac{c}{a}} \right) \tag{5}$$

Where *a,b,c* are regression coefficients; and y(kg/ha) is unit area crop yield.

Considering that the actual crop water consumption might differ from the estimated amount in the conventional water requirement method, we proposed a new water consumption method based on the crop water production function and compared it with the conventional water requirement method. The test showed that on average there was no significant difference between the estimation from the proposed water consumption method and the actual measurement of water use. However, the estimation from the conventional water requirement method was significantly higher than that of the water consumption method or the actual measurement at the Luancheng monitoring station as shown in Supplementary Fig. 1.

2.2.2. WF_{blue} and WF_{green}

WF_{blue} is the volume of consumed surface water and groundwater to produce goods or delivering services. WF_{green} is the volume of consumed rainwater during the production process. WF_{green} is particularly relevant for agricultural and forestry products, including the total rainwater evapotranspiration (from fields and plantations) plus the water incorporated into the harvested products. The WF_{blue} and WF_{green} were calculated by the following equations (Zhang et al., 2008):

$$WF_{cons} = WF_{blue} + WF_{green} \tag{6}$$

$$WF_{blue} = \frac{ET_{blue} \times A \times B}{Y} \tag{7}$$

$$ET_{blue} = \max\left(0, ET_a - P_{eff}\right) \tag{8}$$

$$WF_{green} = \frac{ET_{green} \times A \times B}{Y} \tag{9}$$

$$ET_{green} = \min\left(ET_a, P_{eff}\right) \tag{10}$$

$$P_{eff} = \sigma P \tag{11}$$

Where ET_{blue} (mm) and ET_{green} (mm) are evapotranspiration of blue and green water, respectively; P_{eff} (mm) and P (mm) are effective rainfall and total rainfall within crop growth period, respectively; and σ is the effective utilization coefficient of rainfall.

2.2.3. WF_{grey}

The WF_{grey} is an indicator of freshwater pollution that is associated with a product over its full production chain. It is calculated as the volume of water required to dilute pollutants to meet water quality standards. We focused on the WF_{grey} of nitrogen because fertilizers were used intensively in the NCP and potentially caused the most severe pollution since nitrogen can easily be transported in soil, surface water, and groundwater (Sun et al., 2018). Soil phosphorus often easily generates chemical reactions with other soil minerals and produces chemical compounds that are not readily soluble, resulting in less pollution. Potassium ions are attracted by soil colloids and thus not easily migrated. Therefore, the pollution from phosphorus and potassium fertilizers can be ignored when assessing WF_{grey}. Supplementary Fig. 3 shows that the nitrogen application amount in the NCP, with an average amount of 435.99 kg ha^{-1} and a range from 179.76 to 879.11 kg ha^{-1}. The spatial distributions of fertilizer application for winter wheat and summer maize are similar; however, on average, the nitrogen application amount of winter wheat (223.56 kg ha^{-1}) is higher than that of summer maize (212.43 kg ha^{-1}). The calculation functions for different types of grey WF are shown below:

$$WF_{grey} = \frac{(\alpha_{total} \times AR)/(C_{max} - C_{nat})}{y} \tag{12}$$

Where α_{total} is the total leaching fraction, measured to be 25.0% (Zhao et al., 2009); a_{surf} and a_{ground} are run-off and leaching fractions of applied chemicals for surface water and groundwater respectively, measured as 9.6% and 15.4%, respectively (Xu et al., 2013); AR (kg ha^{-1}) is application amount of chemical fertilizers per hectare; and C_{max} (g L^{-1}) and C_{nat} (g L^{-1}) are the maximum acceptable concentration and natural concentration of the chemical fertilizer, respectively.

2.3. Water scarcity

The water scarcity index of grain production from a WF perspective can be reflected through the ratio of agricultural water use to renewable agricultural water resources (I_{total}). The higher the water scarcity index, the less sustainable water use for grain production. The water scarcity index can be calculated as follows:

$$I_{total} = WF_{grain,\ total} \ / \ WR_{agri,\ total} \tag{13}$$

Where I_{total} is water scarcity due to agricultural use, $I_{total} > 1$ indicates water scarcity and $I_{total} > 2.5$ indicates severe water scarcity due to grain production. $WF_{grain,\ total}$ is the total WF for winter wheat and summer maize here; and $WR_{agri,\ total}$ refers to the renewable agricultural water resources.

2.4. Crop water productivity

Crop water productivity refers to the amount of crop produced per unit of water used. We divided the amount of crop production by its corresponding water footprint in each county in 1986 and 2010 to get the crop water productivity at the county level over time. We also divided crop production by its corresponding water footprint in the whole NCP from 1986 to 2010 to obtain the average crop water productivity for the whole plain over time. To figure out to what extent increasing crop water productivity reduces the water footprint and water scarcity, we set the crop water productivity in 1986 (CWP_{1986}) as the baseline, and recalculated the water scarcity and water footprint during 1987–2010 by multiplying the amount of crop production during 1987–2010 with the CWP_{1986} to get the recalculated WF. Then we divided the recalculated WF from 1987 to 2010 by the renewable agricultural freshwater resource to get the recalculated water scarcity from 1987 to 2010 (Note: the amount of the renewable freshwater resource was kept constant during 1987–2010 since we used the average renewable water resource value across years. The change in water scarcity was determined by the change of WF). Then we compared the original WF and water scarcity with the recalculated WF and water scarcity to calculate the percent decrease in WF and water scarcity due to the change in crop water productivity.

2.5. Statistics and mapping

To test whether or not WF and crop water productivity changed significantly over time, we performed the statistical significance test using the software SPSS Statistics 20 (Statistical Product and Service Solutions, IBM, USA). When P value < 0.05, it indicates a significant change. We acquired GIS shape files for the NCP counties. We created the map of our study areas and mapped all the WF, water scarcity and productivity at the county level in ArcGIS.

3. Results

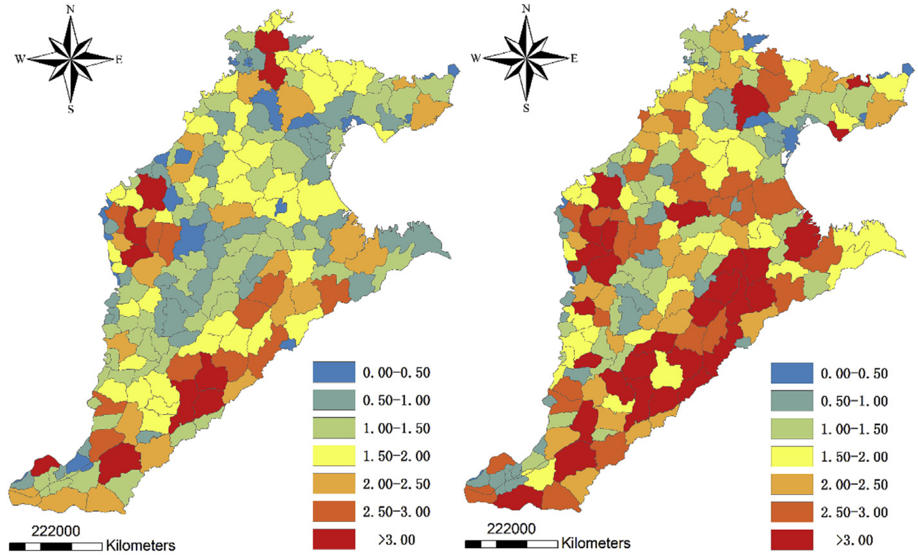
Our results show the annual water footprint from irrigated agriculture increased in almost all counties (Fig. 1). The southeast NCP had a larger water footprint and the central part had a smaller water footprint than other places in the NCP (Fig. 1). Also, the water footprint of southeast NCP increased most while that of the central part increased the least over time (Fig. 1).

The annual water footprint in all counties together increased from 53 billion m^3 in 1986 to 78 billion m^3 in 2010 (Fig. 2a). For the total amount of different types of WF, overall, there were statistically significant increases in WF_{total} ($F = 17.97$, $p = 0.0003$), WF_{green} ($F = 22.17$, $p = 0.0001$), and WF_{grey} ($F = 21.88$, $p = 0.0001$) over time (Fig. 2a; Table 1). The WF_{blue} gradually increased from 1986, peaked in 1997, then started to decline to the valley in 2003, and kept relatively stable between 2004 and 2010 (Fig. 2a). Its overall temporal trend was not statistically significant ($F = 0.31$, $p = 0.5821$; Table 1). There are some potential reasons for the dynamics of the WF_{blue}. During 1986–1997, the rapid development of agriculture led to the WF_{blue} increase. But during 1998–2003, the water-saving policies were implemented in the NCP to reduce planting area and restrict the use of underground water and thus reduced the WF_{blue} (Xie and Zhang, 2007; Liu et al., 2008; Hu et al., 2017). After 2004, the increasing demand for crop production in the NCP compensated for the effects of water-saving policies (Xie and Zhang, 2007; Liu et al., 2008; Hu et al., 2017).

Except for annual WF_{blue}, the whole NCP's annual irrigated agriculture WF, WF_{grey}, and WF_{green} increased due to the overall increase of total crop production over time (Fig. 2b). By comparing Fig. 2a and b, it is easy to observe that the temporal dynamics of total crop production (either winter wheat or summer maize) were similar to the dynamics of WF of irrigated agriculture in NCP. The overall temporal dynamics of different sources of WF_{blue} fluctuated (Fig. 2c).

Irrigated agriculture led to water scarcity in all evaluated counties (use intensity > 1 indicates water scarcity) (Fig. 3). Among the NCP's 207 counties, 174 counties faced severe water scarcity (use intensity > 2.5 indicates severe water scarcity). Our results showed that the average water scarcity for total available water for agricultural use was as high as 10.14, indicating an unsustainable water usage pattern. There were 95.29% counties with severe water scarcity over 5.0 for total available water for agricultural use. Overall, there were 46.5% of counties with total agricultural water use intensity over 10.0 for grain production, covering almost the entire east of NCP (Fig. 3).

Crop water productivity increased in all counties, suggesting an irony with rising water productivity coupled with severe water scarcity (Figs. 4–5). The average crop water productivity increased from 0.90 kg m^{-3} in 1986 to 1.94 kg m^{-3} in 2010. The central and western parts of the NCP had higher crop water productivity while its eastern part had lower crop water productivity. The central part's crop water productivity increased the most, while the eastern crop water productivity increased the least.



(a) (b)

Fig. 1. Spatial dynamics of total water footprint (billion m^3) in irrigated agriculture from 1986 (a) to 2010 (b).

4. Discussion

We find the increasing water footprint – worsening water scarcity while crop water productivity increased – in all 207 counties of the North China Plain over 1986–2010. The results show that the improving crop water productivity had increasingly positive influences on reducing WF and water scarcity over time (Fig. 6). In 1987, an increase in crop water productivity dropped WF and water scarcity 14.5%, and this number increased to 53.7% in 2010 (Fig. 6). However, the total grain production WF was still high and led to water scarcity in all evaluated counties. The underlying reasons for the persistence of water scarcity conditions include the soaring grain production in the NCP driven by rapid economic development and a growing national population, extensive decline in arable areas in south China (Song et al., 2007). With the growing population, an increasing water crisis and anticipated food shortages in the future, the conflict in irrigated agriculture could be exacerbated, posing threats to national sustainability.

Spatial variations in WF of irrigated agriculture across the NCP reveals hotspot areas requiring special management. For example, the southeast part of the NCP showed higher WF than other parts, therefore more agricultural water management should be planned for this area. Southeast NCP produced more crops due to its higher accumulated temperature, greater precipitation, and better soil organic matter than other areas in the NCP (Foster et al., 2004). Furthermore, because of its ineffective agricultural production management, excessive fertilization and waste of water, the southeast's WF was much higher than that in other areas of the NCP. On the other hand, the comparatively slow-growing crop productions WF in the central NCP was less than other parts of NCP. Since 1980, the government controls the agricultural production in the central part of the NCP to limit the groundwater exploitation because a groundwater funnel emerged (Wang et al., 2015). Moreover, since the precipitation in the central part of the NCP is smaller than that in other regions, the WF is much smaller because only this available precipitation is consumed.

Water transfer projects such as the South-North Water Transfer Project (Liu and Yang, 2012) (SNWTP; the largest water transfer project in the world with a planned total investment of $80 billion USD and annual transfer amount of 48.4 billion m^3 water) has mixed impacts. By transferring physical water from southern China to northern China, the SNWTP can help alleviate the water shortages in northern China and indirectly enhance national food security. But the environmental cost of SNWTP is also large (Yin et al., 2001; Shao et al., 2003; Zhang, 2009; Liu et al., 2016). Therefore, for the NCP and China as a whole, the long-term water management strategies should target controlling and reducing total water use by improving water use efficiency rather than constructing more engineering projects to support the seemingly endless demand for water.

There are also many other specific measures to reduce total water consumption from grain production in the NCP. For instance, the total WF of NCP can be reduced by importing grain and other food products from water-abundant countries and reducing the cultivation area in the NCP. One way to reduce total WF is to mitigate WF_{grey}, which is the highest priority since it accounts for a large percentage of the total WF. The primary reasons for high WF_{grey} in the NCP are overuse and low efficiency in applying chemical fertilizers and pesticides. For example, the average per unit area amount of nitrogen applied (545 kg ha^{-1}) in a wheat-maize rotation system in the NCP during 1997–2005 was much higher than the nitrogen output within harvested crops of system (311 kg ha^{-1}) (Zhao et al., 2009), meaning some nitrogen ended up polluting rather than boosting crop growth. Many studies (Ju et al., 2003; Zhang et al., 2006; Zhang, 2011) suggest that the applied amount of fertilizers and their use efficiency is negatively correlated, and thus controlling the use of fertilizers and improving their use efficiency are complementary. Using straw, livestock manure, biogas waste, and organic fertilizers instead of chemical fertilizers can not only reduce the applied amount of chemical fertilizers but also increase crop yield in the NCP (Zhang et al., 2006). Many nutrient management techniques, such as balanced fertilization, soil testing and formulated fertilization, application of slow-release fertilizers, and selection of fertilization timing, can also improve the use efficiency (Zhang et al., 2006; Quiñones et al., 2007; Zhang, 2011).

And crop production conditions can be altered (e.g., cultivar, water use efficiency, irrigation, and tillage methods) to change the

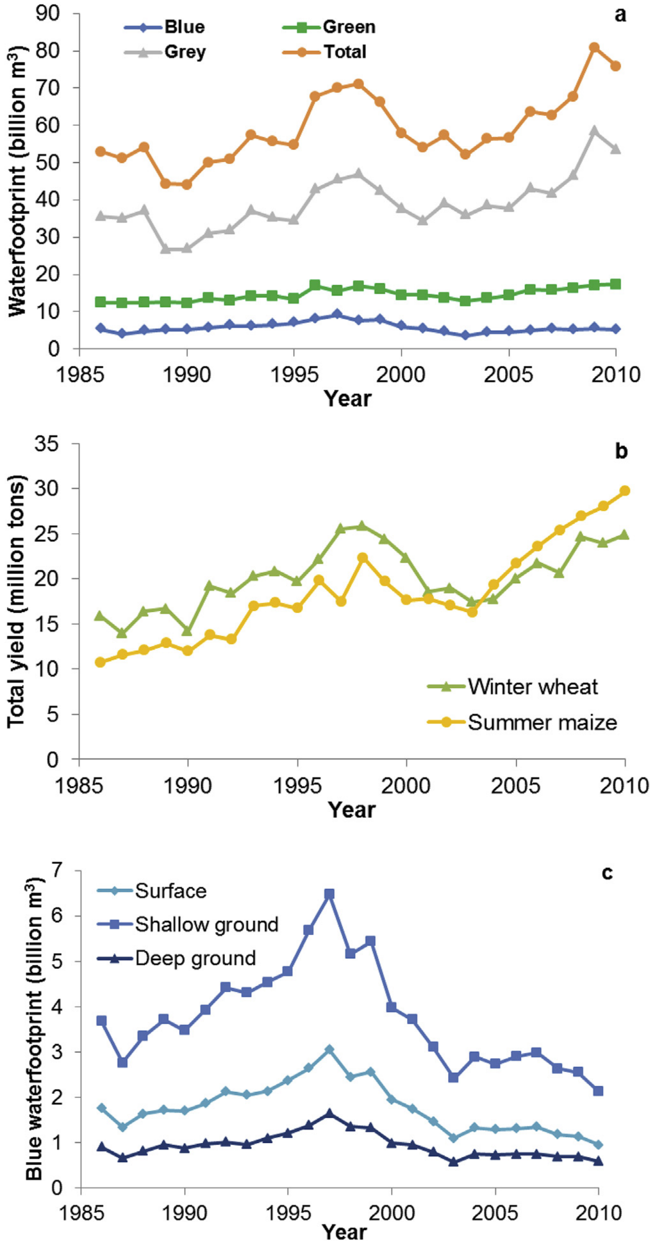


Fig. 2. Temporal dynamics of different types of water footprint and annual total grain yield from 1986 to 2010. (a) The different types of grain production water footprint; (b) the total annual grain yield; and (c) the different sources of blue water footprint. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

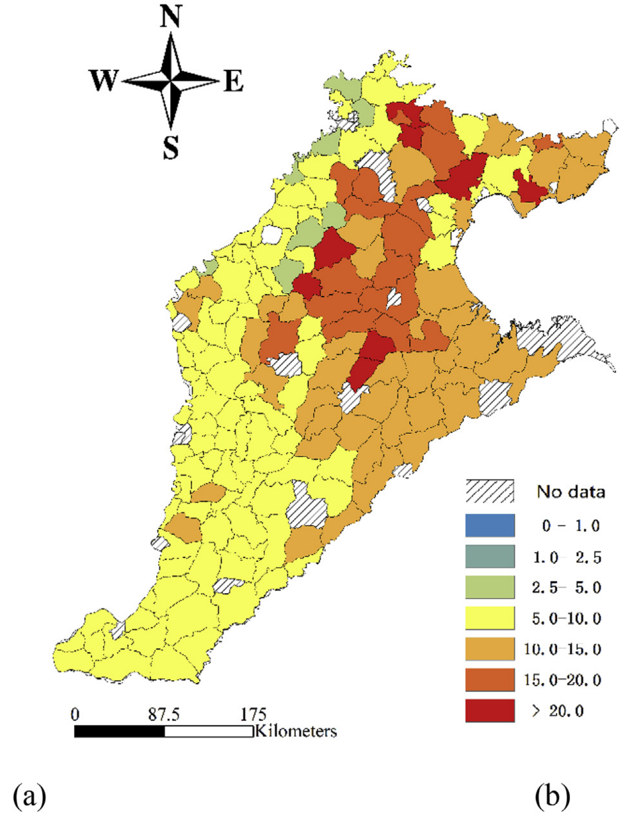


Fig. 3. Spatial dynamics of water scarcity in irrigated agriculture from the water footprint perspective. Index greater 1 indicates unsustainable water use.

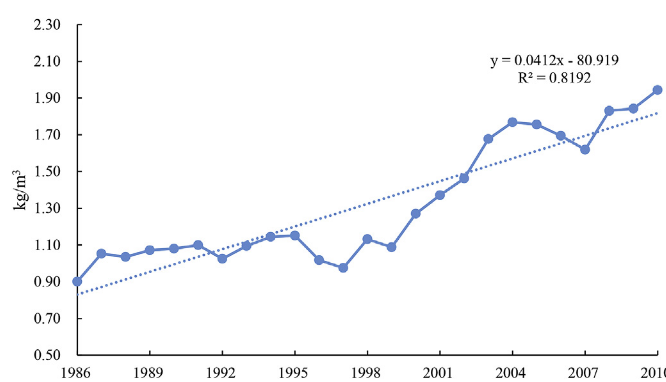


Fig. 4. Temporal dynamics of average crop water productivity (kg/m^3) in the NCP from 1986 to 2010.

Table 1
Temporal trend analyses of grain production water footprint from 1986 to 2010 based on regression lines.

	WF_{total}	WF_{blue}	WF_{green}	WF_{grey}
Year	0.843*** (0.181)	−0.021 (0.027)	0.161*** (0.023)	0.703*** (0.164)
Constant	−1624.341*** (361.346)	47.299 (53.088)	−306.696*** (45.378)	−1364.944*** (327.980)
F statistics	21.65	0.62	49.89	18.29
R-Squared	0.44	0.01	0.49	0.49
N	25	25	25	25

Notes: Dependent variables are different types of grain production water footprint (10^9 m^3) in average values for the 207 analyzed counties, respectively. Numbers outside and inside parentheses are coefficients and robust standard errors, respectively. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

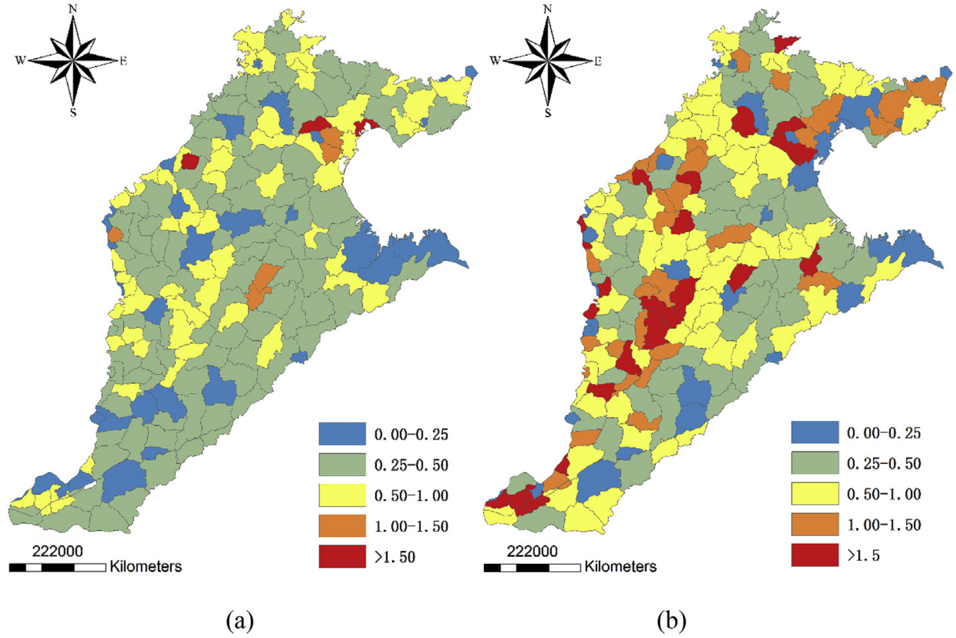


Fig. 5. Spatial dynamics of crop water productivity (kg/m^3) in irrigated agriculture from 1986 (a) to 2010 (b).

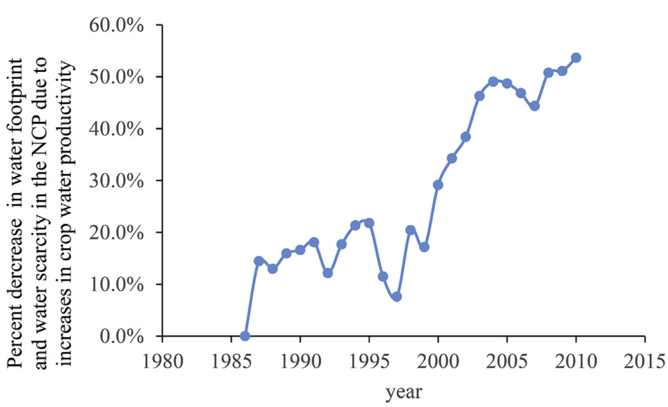


Fig. 6. Percent decrease in water footprint and water scarcity in the NCP due to increases in crop water productivity from 1986 to 2010.

WF. The WF can be reduced by increasing per unit area crop yield or decreasing actual crop evapotranspiration. Field experiments confirm that using high yield cultivar improved crop water productivity and reduced water consumption (Zhang et al., 2010). Many techniques below are also documented to improve water use efficiency and thus reduce actual crop evapotranspiration. Currently, the common irrigation approach in the NCP is still surface irrigation with very low use efficiency of both water and fertilizers. The combination of integrated irrigation and fertilization technique with efficient water-saving irrigation systems (e.g., sprinkler irrigation, micro-irrigation) can reduce surface erosion, retain fertilizers in the crop root zone, mitigate fertilizers leaching into underground (Liu and Kang, 2006; Man et al., 2014), and thus reduce both WF_{grey} and WF_{blue}. Research shows that the deficit irrigation approach and appropriate reduction of irrigation times for winter wheat can maintain or only slightly reduce crop yield but largely increase water use efficiency (Yang et al., 2006; Zhang et al., 2008). Covering the soil with straw can reduce soil evaporation while increasing rainfall infiltration and reducing surface runoff (Li et al., 2013). The use of soil tillage and subsoil tillage methods can improve soil moisture holding capacity, reduce ground infiltration, and increase water use efficiency (Salem et al., 2015). Greenhouse agriculture (e.g., covering the field with plastic films is much more common than glass greenhouses in China) also helps reduce water evaporation and water use (Chang et al., 2011).

Our work provides the first detailed and integrated assessment that analyzes water footprint, water scarcity, and crop water productivity at the county level in a large plain over long term. It reveals the serious unsustainable water use across all counties in the NCP. The spatial variations of unsustainable water use, water footprint, and crop productivity are disclosed. This information can help the government make more holistic and better-targeted policies to manage crop production and water consumption more sustainably in China's major crop production region. Future research can focus on the interactions between irrigated agriculture in the NCP and the environmental and socioeconomic development in the rest of China. Since much of the NCP harvest was transferred to the rest of China to enhance food security, and since much water was diverted from southern China through SNWTP to the NCP to alleviate the water shortage, the interactions between these two systems are complex and have great impacts on both systems. Cross-boundary studies can help get a comprehensive picture of drivers behind water use and thus provide holistic information for policy-making, therefore facilitating sustainable development and improvement of human well-being (Liu 2017, 2018).

5. Conclusions

In this paper, we quantified water footprint, crop water productivity, and water scarcity from irrigated agriculture in China's major crop production region, the North China Plain's 207 counties, from 1986 to 2010. Our results indicated that even though crop water productivity grew over time, the water footprint in the NCP due to crop production increased sharply from 53 billion m3 in 1986 to 78 billion m3 in 2010, leading to water scarcity in all 207 counties. This study revealed the unsustainable state of irrigated agriculture in China's major crop production region, which has implications for global irrigated agriculture at the county level. The irrigated agriculture enhanced food security but increased the pressure on water use. There is tremendous pressure on water resources due to a huge food demand on the NCP under the context of a growing national population. Changing high water consumption cropping systems, developing efficient water-saving irrigation technology and reducing cropland area should be considered for the future agricultural management to help ensure water security and food security simultaneously.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.03.108.

Author contributions

Z.X., Y.L. and J.L. designed the research; Y.L., and X.C. contributed data; X.C., M.G., S.R.W., Y.D, J.W. and J.L. provided comments on the manuscript; Z.X., and X.C. analyzed the data and wrote the manuscript. All authors reviewed the manuscript.

Competing financial interests

The authors declare no competing financial interests.

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