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Changes in water use efficiency and water footprint in grain production over the past 35 years: a case study in the North China Plain

Yang Lu [a, b], Xiying Zhang [a, *], Suying Chen [a], Liwei Shao [a], Hongyong Sun [a]

[a] The Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, The Chinese Academy of Sciences, Shijiazhuang 050021, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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A B S T R A C T

Water use efficiency (WUE, defined as the ratio of grain yield divided by the crop water use) considers the water used directly in the field. Water footprint (WF, calculated as the sum of green, blue and grey WF) also includes the water use of farm inputs and the possible environmental effects of crop water use. This study used the two metrics to assess the WUE and WF of winter wheat and summer maize, an annual double cropping system in the North China Plain (NCP), using field data collected at a fixed site from 1980 to 2014 as a case study. The results show that there was seasonal variation in the WUE and WF of winter wheat and summer maize in response to fluctuations in grain production and farm inputs. Annual average WUE was increased from 1.21 kg m^{-3} in 1980s to 1.80 kg m^{-3} recently, and the annual average WF was decreased from 0.90 m^{-3} kg to 0.78 m^{-3} kg. The contribution of the WF_{green}, WF_{blue} and WF_{grey} to total WF was 23.4%, 62.0% and 14.5% for winter wheat, and 59.4%, 26.7% and 14.0% on average for summer maize, respectively. The WF_{blue} took up about half of the WF, indicating the dependence of grain production on irrigation in this region. The results from this study also showed that the increase in WUE was much greater than the decrease in WF due to the fast increase in WF_{grey}. The continuous increase in farm inputs from 1980s to present offset some improvement in crop water productivity. The WF metric can not only quantify the consumptive water use, but also evaluate the environmental impacts related to entire agricultural production systems. Thus, WF measure may be a more comprehensive approach than that of WUE in assessing the effectiveness of crop water use and its environmental influence.

1. Introduction

Freshwater availability has a significant impact on food security, because water plays a critical role in food production (Ridoutt et al., 2009). Hoekstra and Mekonnen (2012) found that agriculture accounts for 92% of total freshwater use; irrigation is responsible for approximately 70% of all freshwater withdrawals globally (Ridoutt et al., 2009). Increasing crop water productivity will be a crucial strategy for addressing agricultural water shortages (Levidow et al., 2014). The water use efficiency (WUE) is usually used as an indicator to assess water usage in a unit of agricultural production and therefore, the effectiveness of crop water use. WUE is generally defined as the ratio of the crop yield over the seasonal actual evapotranspiration (Howell, 2001; Morell et al., 2011; Nyakudya and Stroosnijder, 2014). Many studies have demonstrated temporal and spatial differences in the global WUE (Du et al., 2010). The WUE is affected by many factors, e.g., cultivars, management, climate and so on, and it provides a mean to assess the effect of different management practices on crop water use efficiency (Zhang et al., 2011).

The North China Plain (NCP) is one of the most important grain producing regions in China. The annual rainfall in the NCP is approximately 500 mm. The most common double-cropping system in the region, comprised of winter wheat and summer maize, consumes 800–850 mm of water annually (Yang et al., 2015). Irrigation is very important to the production of high yields in these two crops. A large proportion of irrigation water comes from underground reservoirs, resulting in the rapid depletion of the

* Corresponding author. Tel.: +86 311 85871762; fax: +86 311 85815093.
E-mail address: xyzhang@sjziam.ac.cn (X. Zhang).

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groundwater table, which threatens the sustainability of agricultural development in the region (Sun et al., 2010; Zhang et al., 2006). Solving the water shortage problem has been the focus of many studies (e.g. Kendy et al., 2003; Sun et al., 2010; Xu et al., 2015). Improving WUE by maintaining or increasing grain production and simultaneously reducing the use of irrigation water is critical for sustainable agricultural development in the NCP. Zhang et al. (2011, 2013) conducted a 30-year irrigation experiment on winter wheat and summer maize to analyze the variation in the WUE of the two crops and its relationship with weather and management practices. They found that there was an annual increase in the WUE of 0.014 kg m^{-3} for winter wheat and 0.032 kg m^{-3} for summer maize. With new cultivars and improved management practices it was possible to increase grain production without much increase in water use. This is critical for addressing the dual issues of regional water scarcity and the food demands of a growing population.

Although WUE is widely used, it does not take into account the impacts of freshwater water use on the environment (Page et al., 2011; Wang et al., 2014) and does not consider the effects of agricultural production inputs. The water footprint (WF), which integrates quantitative and qualitative water use, considers not only the direct water consumption of food production in the field, but also the water consumption throughout the whole process of producing a certain food, as well as the environmental effects of the water consumption. The WF is a strategic and effective tool to assess crop water use (García Morillo et al., 2015). The WF concept was developed by Hoekstra (2003). Analogous to the carbon footprint and ecological footprint, WF is one of the "family of footprints" (Galli et al., 2012); it usually includes green water (precipitation consumed by crop evapotranspiration), blue water (surface and groundwater resources consumed during the whole agrifood product life cycles) and grey water (the volume of freshwater required to assimilate the emission of farm inputs into freshwater) (Hoekstra et al., 2011). To achieve a better measure of real water use, the consumptive water use of farm inputs during crop production is also considered. The green water footprint (WF_{green}) or blue water footprint (WF_{blue}) is expressed as a single volumetric value referring to the water consumed for production in a specific space and time (Huang et al., 2012; Sun et al., 2013b), while the grey water footprint (WF_{grey}) refers to the volume of water needed to dilute pollutants to agreed water quality standards (Jeswani and Azapagic, 2011). Because of this integration, the WF reflects the potential impact of several different consumptive water uses on the environment (Hoekstra, 2003). Therefore, WF can be used to assess both the changes in water use within agriculture and its environmental effects.

Therefore, the aims of this study were: (1) to evaluate the temporal variation of the evapotranspiration (ET, also defined as the direct water use), crop yield, indirect consumptive water (ICW) and WUE of winter wheat and summer maize under local irrigation scheduling in the NCP; (2) to quantify the WF_{green}, WF_{blue}, WF_{grey} changes for winter wheat and summer maize; (3) to examine the critical factors affecting the changes in WUE and green, blue, and grey WF for the two crops. In addition, by comparing the ability of WUE and WF to evaluate the impacts of changes in management practices and crop productivity on crop water use and its environmental effects could provide references for better water management in crop production.

2. Material and methods

For this study, direct and indirect water use for winter wheat and summer maize from a fixed site in NCP were used to analyze the changes in WUE and WF for the recent 35 years.

2.1. Experimental site

This study was carried out on a field at the Luancheng Agroecosystem Experimental Station (simplified as Luancheng station), located in the northern part of the NCP (50 m above sea level, 37°53′N and 114°40′E). The soil, weather and field management practices for the field were representative of the surrounding areas and can be taken as a case study of the northern part of NCP. Results from the long-term field monitoring beginning in 1980 was used to analyze the changes in the WUE and WF of a winter wheat–summer maize double-cropping system for the past 35 years (1980–2014). The average annual precipitation was approximately 480 mm at the station, with rainfall of approximately 100–150 mm during the winter wheat season and 300–380 mm during the summer maize season. Irrigation played a vital role in securing high yields of the two crops. Generally, irrigation was applied to winter wheat 3–4 times in a season and to summer maize 1–2 times to maintain the soil water content above 65% of the field capacity for the main root zone profile and to ensure that no serious water deficit occurred. This treatment, defined by sufficient irrigation scheduling, was regarded as the common irrigation scheduling in the study region.

2.2. Changes in management practices

The management practices of the two crops changed with time. In the 1980s, winter wheat and summer maize straw was removed from the field manually. Before the winter wheat was sown, the soil was cultivated using a plough mounted on a tractor. Summer maize was sown directly into the soil manually, without cultivation. In the 1990s, winter wheat was harvested by combine and the winter wheat straw was left in the field as mulch, to replace manual harvesting. The summer maize straw was removed. Beginning in the late 1990s, the summer maize straw was chopped and incorporated into the topsoil layer, without being removed. With the changes in tillage practices, machinery inputs changed continuously.

The input in chemical fertilizer was gradually increased over the past 35 years. The annual application amount for N was around 150–250 kg ha^{-1} in 1980s, 250–300 kg ha^{-1} in 1990s and 300–430 kg ha^{-1} recently. It was 90–100 kg ha^{-1}, 100–130 kg ha^{-1} and 130–240 kg ha^{-1} for P_2O_5, respectively, for the three periods. Beginning at the earlier of 2000s, K_2O was also added at the rate around 20 kg ha^{-1}. It was increased to 90 kg ha^{-1} recently. The use in pesticides was also increased gradually. Table 1 lists the changes in annual inputs including chemical fertilizer, pesticides, the diesel consumption of the machinery and the electricity used for irrigation during the three periods. The crop cultivars used were all local commonly used varieties.

2.3. Data collection

Agricultural input data including fertilizers (N, P_2O_5 and K_2O), seeds, pesticides, fuel and electricity were recorded separately for winter wheat and summer maize. The sum of the input for the two crops in the same year was taken as annual input (from the beginning of October to the end of September next year). The boundaries of the agricultural input for each crop were taken as from the harvesting of the previous crop to the harvesting of the crop itself. The machinery input was calculated as fuel consumption. The input in pumping water for irrigation was calculated as electricity consumption. The labour input was not considered in this study.

The daily rainfall data was collected from a standard weather station nearby the experimental field, which was used to calculate