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Water footprint assessment for crop production based on field measurements: A case study of irrigated paddy rice in East China

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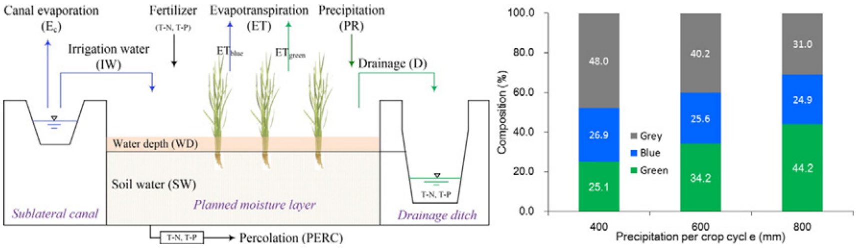
HIGHLIGHTS

- Water footprint was measured along with water and fertilizer utilization processes on farmland.
- Grey water footprint was the major part of water footprint of paddy rice.
- Changes of precipitation did not affect total water footprint, but changed its composition and made production more clean.

GRAPHICAL ABSTRACT



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ABSTRACT

Water footprint (WF) is a comprehensive measure of water consumption by human activities and can be used to assess the impact on both water volume and quality. This study aims to explore the feasibility of evaluating green, blue and grey WFs of crop production based on field measurements. The irrigated paddy rice grown in three different experimental sites in different typical irrigation districts in Huai'an, East China over 2011 to 2014 was taken as study case. With fixed irrigation and fertilization, on the basis of measuring field water and fertilizer balance at daily step, we calculated WF of crop production under different test treatments. Results show that crop water requirement of rice was measured as 667.1 mm and 6.2% of the total nitrogen (T-N) was washed away from farmland accompany with drainage and percolation. Average annual WF of paddy rice during 2011–2014 in Huai'an was 1.760 m^3/kg (33.3% green, 25.8% blue and 40.9% grey). The level of WF and blue water proportion in different locations (irrigation districts) and different years changed slightly, while the proportion of green and grey WF changed with the variance of precipitation. Green water proportion was 25.1%, 34.2 and 44.2%, while 48.0%, 40.2% and 31.0% for grey water proportion under precipitation levels of 400, 600

Abbreviations: WF, Water footprint; blue WF, WF_{blue}, Blue water footprint; green WF, WF_{green}, Green water footprint; grey WF, WF_{grey}, Grey water footprint; ET, Evapotranspiration; WD, Field water depth; IW, Irrigation water; D, Drainage; PERC, Percolation; IE, Irrigation efficiency; U_f, Field water utilization coefficient; T-N, Total nitrogen; T-P, Total phosphorus; $C_{max, N}$, Highest permissible concentration for T-N; $C_{max, P}$, Highest permissible concentration for T-P; E_c, Canal evaporation; CWU, Crop water use; CWU_{blue}, Crop blue water use; CWU_{green}, Crop green water use; $WR_{dilution}$, Dilution water requirement; Y, Crop yield; ET_{blue}, Field blue/irrigation water evapotranspiration; IW_{gross}, Gross irrigation water; ET_{green}, Field green/rain water evapotranspiration; S, Total sewage discharge; $WR_{dilution, N}$, Water required to dilute the T-N concentration; $WR_{dilution, P}$, Water required to dilute the T-P concentration; WP, Water productivity; WA, Water appropriation; TWU, Total water use; GI, Gross inflow; FWP, Water productivity of WF; IWP, Irrigation water productivity; TWP, Water productivity of total water use; GWP, Water productivity of gross runoff; EWP, Water productivity of evapotranspiration.

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Field measurement
East China

and 800 mm, respectively. The reduced grey WF was due to increased drainage. This study not only proved the feasibility of assessing WF of crop production with field experiments, but also provided a new method for WF calculation based on field water and fertilizer migration processes.

1. Introduction

Water shortage and agricultural non-point source pollution are universal problems facing the world. With an increasing demand for agricultural products, mankind has promoted food production through the expansion of irrigated area and increase of fertilization application in the limited land resources (Falkenmark, 2001; Cao et al., 2015a). The limitation and shortage of water resources have become key constraints in the development of irrigation. At the same time, agricultural non-point source pollution caused by large amount of fertilizer use is affecting the quality of land and water resources. These problems are particularly serious in China, an important developing country with the largest population (Liu et al., 2008; Sun et al., 2012; Cao et al., 2017). Objective evaluation of real water consumption and associated effects on water quality by crop production are reliable ways to promote an efficient and sustainable use of water resources in agriculture.

Water footprint (WF) is a comprehensive measure of water consumption by human activities and can be used to assess the impact on both water volume and quality (Hoekstra et al., 2011; Zeng et al., 2013; Pellicer-Martínez and Martínez-Paz, 2016; Scherer and Pfister, 2016). WF of crop production is the volume of fresh water that is consumed during the crop growing period and has three components: green, blue and grey WFs. Blue and green WFs in crop production are consumptive WF and refers to the total evapotranspiration (ET) during the crop growth period. Grey WF, which is also known as degradable WF, refers to the volume of freshwater that is required to assimilate the load of pollutants caused by fertilizer leaching given natural background concentrations and existing ambient water quality standards (Hoekstra et al., 2011; Cao et al., 2017). In view of the advantages of WF, the research on WF of crop production has become a hot research topic. WF of crop production evaluation has been conducted in multiple regional scales from an irrigation district (Sun et al., 2013a; Cao et al., 2014a; Suttayakul et al., 2016), a city level region (Sun et al., 2013b; Xu et al., 2015; Marano and Filippi, 2015; Su et al., 2015; Lu et al., 2016; Chu et al., 2017), a river basin (Idaya and Llamas, 2008; Zeng et al., 2012; Bocchiola et al., 2013; Zhuo et al., 2016a; Denis et al., 2016; Roux et al., 2017), a country (Ma et al., 2006; Kampman and Hoekstra, 2008; Bulsink et al., 2010; W. Wang et al., 2014a; Y. Wang et al., 2014b; Cao et al., 2014b; Wang et al., 2015; Zhuo et al., 2016b) to the global perspective (Siebert and Döll, 2010; Mekonnen and Hoekstra, 2011, 2014; Hoekstra and Mekonnen, 2012; Lovarelli et al., 2016). Published studies have been adequately addressed in terms of crop types and research scales. WF values for 126 crops and derived crop products at provincial level of the world during 1996 to 2005 can be easily gained according to Mekonnen and Hoekstra (2010). However, almost all reported value of WF of crop production in the previous studies was obtained through models of many types, including hydrological model, water balance model and crop water productivity model. They were all more or less based on assumptions on inputs that resulted in uncertainties across different models as well as among certain individual estimations (Mekonnen and Hoekstra, 2011; Zhuo et al., 2014; Tuninetti et al., 2015). Although modelling is efficient in time and economy to measure costs for large scale WF assessment, field measurement is the base for parameter calibration, uncertainty reduction and result validation of modelling work (Johannessen et al., 2015). Meanwhile, WF assessment for a small area, especially an irrigation area or a specific farmland, real-time measurement of WF related parameter is clearly more accurate than the simulation results by modelling and can give more reference for individual farmers. Only a few number of scholars have begun to explore field measurement methods for WF of crop production and its feasibility in recent years. Herath et al. (2014) reported, for the first time, consumptive WF and grey WF of rain-fed potato grown areas in the Manawatu region of New Zealand based on measured soil water content, drainage under potatoes and analysis of nitrate nitrogen concentration using tension flux meters at experimental field. Castellanos et al. (2016) estimated grey WF of irrigated melon crop in the semi-arid areas in Spain based on field measured nitrate leaching by porous ceramic cups. The above relevant literature mainly pay attention to commercial crops. However, the three types of staple food crops—rice, wheat and maize—account for 38% of total WF of crop production of the world (Mekonnen and Hoekstra, 2011) did not receive much attention. Therefore, this paper provides an empirical study of the green, blue and grey WF of a staple food crop at field.

With global total output of 950 M ton per year, rice is one of the major crops feeding the global population and is the most important ration composition in China. It also accounted for 32.5% of Chinese grain crop sown area and 37.6% of grain production during 2011–2014. Paddy rice is not only the largest water consumer in China, but also the most important origin of agricultural non-point source pollution (Ongley et al., 2010). A majority of rice in the country cultivated in southeast provinces and almost all of the irrigation projects are constructed to meet the water demand of rice production in East China (Wang et al., 2013). In this paper, irrigated paddy rice in East China was studied, and a field measurement based method differed from previous studies were introduced for WF assessment was tested. This paper fills the gap in the study of crop types, provides a more optional field measurement program for estimate WF of crop production from the view of cost and condition.

2. Methodology

2.1. Study area

This paper takes rice in Huai'an region of Jiangsu province in eastern China as its subject. Huai'an is located in central Jiangsu province and is an important rice production base in this province (Fig. 1). The annual sown area and output of rice paddy in this region were about 0.3 M ha and 2.5 M ton, respectively in the year of 2014. In order to obtain as many sample data as possible, three experimental plots were set up in three typical irrigation districts named Lianxi Irrigation District (LID) of Lianshui County, Huailian Irrigation District (HID) of Huaiyin County and Qingshuiba (QID) in Xuyi County, respectively. Continuous observations were made from 2011 to 2014. With the growing period of 125–131 days, rice in the study area was planted in late June and harvested in late October. Locations of study area and experimental plots were mapped in Fig. 1 and the basic situation of each observation point is listed in Table S1.

2.2. Field experiments

Each experimental plot consists of three cells with a length of 72 m and a width of 20 m. Irrigation canal and drainage ditch are 1.5 and 2.0 m wide, respectively. The middle of each cell is equipped with a micro-lysimeter (0.5 m × 0.5 m × 1.0 m). An observation well (diameter 5.0 cm and 1.2 m depth) was installed in each cell. Experimental plot and layout of cells are shown in Fig. 2. Shallow and frequent irrigation