Agricultural Water Management 197 (2018) 100–109

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Winter wheat water requirement and utilization efficiency under simulated climate change conditions: A Penman-Monteith model evaluation

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ARTICLE INFO

Article history:
Received 22 March 2017
Received in revised form 4 October 2017
Accepted 24 November 2017

Keywords:
Climate change
Free-Air CO_2 enrichment (FACE)
Elevated temperature
Water utilization efficiency
Winter wheat
Crop water use

ABSTRACT

Impact of climate change on water supply and use is a critical issue for dryland crop production. In this study is assessed the potential impact of atmospheric CO_2 enrichment (500 μmol mol^{-1}, CE) and canopy warming (+2 °C, WA) and their combination (CW) on crop water utilization efficiency (*WUE*) of winter wheat in an open-air field experiment from Southeast China. Micro-meteorological measurement and wheat growth under individual treatments over three executive years of 2012–2015 were used to estimate the crop water requirement (*CWR*) of wheat using an improved FAO Penman-Monteith equation. Overall, CO_2 enrichment slightly decreased the *CWR* by 8.3%, and increased the *WUE* of grain production (*WUEg*) by 23.1%, averaged over the three years. In contrast, warming increased *CWR* by 19.6% but decreased *WUEg* by 27.9% over the period. Under CW treatment, however, *CWR* was increased by 3.1–15.8% but *WUEg* was decreased by 3.5–18.2% throughout three years. Clearly, the positive impact of CO_2 enrichment on *WUE* was largely negated under canopy warming. Moreover, when assessing with individual year data, inter-annual variability of *WUEg* was insignificant under WA, smaller under CE but much higher under CW, compared to CK. These results indicated that an interaction by canopy warming overshadowed the potential increase in *WUE* with CO_2 enrichment and enforced yearly fluctuation of the crop production under simulated climate change conditions. Therefore, improving water supply and management in agriculture should thus be endeavored to address the potential constraints with future trends of concurrent atmospheric CO_2 enrichment and warming.

1. Introduction

World agriculture consumes about 70% of the world's freshwater and food security exerts a strong dependence on water resource availability (Bocchiola et al., 2013; Fader et al., 2011; Konar et al., 2011; Palazzoli et al., 2015). Water resource shortage has been increasingly constraining crop production (Piao et al., 2010; Wallace, 2000), challenged with the global climate change (Rosenzweig et al., 2014; Wheeler and von Braun, 2013). Increasing water utilization efficiency (*WUE*) would be a priority task among the key measures to sustaining global crop production in the coming decades (Elliott et al., 2014; Hoekstra and Mekonnen, 2012; Iglesias and Garrote, 2015; Ye et al., 2015). As one of most important non-irrigated staple crops (Ladha, 2003), winter wheat production has been constrained by decline in water availability with increasing drought frequency in recent years. Therefore, technologies to increase *WUE* would be measures to enhance climate-smart agriculture (Paustian et al., 2016).

Global atmospheric CO_2 concentration is expected to increase over 500 μmol mol^{-1}, while surface air temperature to elevate by about 2 °C during the middle of 21st century (IPCC, 2013; Solomon et al., 2009). This climate change would have great impacts on crop production (Guo et al., 2010; O'Leary et al., 2015), potentially through decreasing *WUE* by plants (Wallace, 2000). However, the impacts on crop water utilization could vary with climatic factors that influence the evapotranspiration and plant physiological processes. Elevated CO_2 concentration tends to decrease transpiration and seasonal crop water requirement (*CWR*) owing to decreased stomatal conductance (Shimono et al., 2013; Yu et al., 2007). Being often addressed as CO_2 fertilization effect, CO_2 enrichment could increase plant biomass and grain production, resulting in an apparent increase in *WUE* (Bunce, 2013; Hunsaker et al., 2000; O'Leary

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https://doi.org/10.1016/j.agwat.2017.11.015
0378-3774/© 2017 Published by Elsevier B.V.

et al., 2015; Shimono et al., 2013; Yoshimoto et al., 2005). However, CO_2 enrichment could also negatively affect *CWR* for the potential increase in leaf area index (LAI) (Kim et al., 2003; Shimono et al., 2013) and photosynthetic rate (Ruiz-Vera et al., 2013). On the other hand, CO_2 enrichment could result in an increase in air temperature, which would generally increase *CWR* since evaporation and canopy transpiration could be increased (Goyal, 2004), and thus crop productivity decreased (Wang et al., 2016a) under elevated temperature. Meanwhile, elevated temperature could induce a shortened duration of crop growing (Cleland et al., 2007) and thus a decreased crop *CWR*. The net response of crop production to the combined effects of CO_2 enrichment and warming has been evaluated in previous studies (Kim et al., 1996; Ruiz-Vera et al., 2013; Usui et al., 2016), the majority of which suggested that the positive effect of CO_2 enrichment was often traded off by the negative effects of warming on crop production (Hasegawa et al., 2017; Wang et al., 2016a). Therefore, it is worthy to address the combined effects of CO_2 enrichment and warming on *CWR* and *WUE* under field conditions.

Modelling approaches had been employed in evaluating inter-annual variability of water consumption by crop in response to climate change conditions (Cammarano et al., 2016; O'Leary et al., 2015; Zhuo et al., 2014). Crop *WUE* was modeled to increase in a range of 7% to 120% between years under CO_2 enrichment in field and greenhouse studies (Hunsaker et al., 2000; Niu et al., 2011; Shimono et al., 2013; Tausz-Posch et al., 2013; Wu et al., 2004). In a modelling study by Cammarano et al. (2016), elevated temperature increased annual variability of *CWR*, regardless of CO_2 enrichment effects. However, large uncertainties existed among the modelling predictions of *CWR* or *WUE*, for the lack of field observations (Cammarano et al., 2016; Li et al., 2015). Therefore, to what extent the different climate change scenarios would impact the inter-annual variability of *CWR* and *WUE* is still unclear.

So far, over 50 mathematical estimations had been used for predicting evapotranspiration (ET) and *CWR*, with varying complexity using different variables (Lu et al., 2005; Islam et al., 2012). As recommended as a standard method of water requirement calculation by the International Commission on Irrigation and Drainage (ICID) and Food and Agricultural Organization of the United Nations (FAO), the use of the Penman-Monteith model directly incorporates the relevant meteorological variables and biophysical parameters (Allen et al., 1998). Later on, Penman-Monteith model had been concerned as the most reliable model worldwide (Kingston et al., 2009; Lu et al., 2005). Changes in atmospheric CO_2 concentration and temperature could modify the relevant physiological traits (e.g., leaf area, stomatal conductance) and also meteorological variables (e.g., temperature, rainfall, relative air humidity) of cropland, which are important for ET. Kingston et al. (2009) argued that Panman-Monteith was most reliable method among the six methods including Penman-Monteith, Hamon, Hargreaves, Priestley-Taylor, Blaney-Criddle, and Jensen-Haise models, when assessing potential ET. This model was constructed on a robust physical basis with all relevant meteorological variables and allowed to address non-meteorological uncertainties such as specification of canopy conductance.

The Penman-Menteith model had been also preferable for future climate change impact studies, for the model addresses changes rather in atmospheric variables than in edaphic conditions (Islam et al., 2012; Kingston et al., 2009). By modifying the canopy resistance term, Penman-Monteith model could effectively evaluate the impacts of global warming and CO_2 enrichment on ET (Islam et al., 2012; Priya et al., 2014; Wu et al., 2012). Therefore, Penman-Monteith model could directly be used to simulate ET and evaluate *CWR*. Moreover, the Penman-Monteith equation had been widely used to estimate crop evapotranspiration and water demand in simulated climate change experiments (Cammarano et al., 2016; Ewert et al., 2002; Goyal, 2004; Lovelli et al., 2010; Savabi and Stockle, 2001; Steduto et al., 2009).

China is one of the major crop production countries in the world (Frolking et al., 2002), of which the food safety is vulnerable global change and the associated extreme weather events (Lesk et al., 2016; Pan, 2010; Ray et al., 2015). Rice and wheat production from Asia could be greatly impacted by climate change conditions, possibly enhanced under CO_2 enrichment but negatively impacted by global warming (Hasegawa et al., 2017; Wang et al., 2016a). At particular, drought and water scarcity had become key constraints for crop production of China (Piao et al., 2010). To understand the effects of climate change on *CWR* and *WUE* is a prerequisite for developing such climate-smart agriculture of China.

So far, it remains unclear whether the effect of warming outweighed the effect of CO_2 enrichment in terms of *CWR* and *WUE*. This limits our ability to predict the potential impact of climate change on wheat productivity. We hypothesize that wheat *CWR* or *WUE* could vary with different sets of climate change conditions and exert inter-annual variability between years of the climate change simulation. Based on micro-meteorological data collected over three consecutive years from an open air field experiment in Southeast China, this study is to estimate the combined effects of CO_2 enrichment and warming on the status and stability of *CWR* and *WUE* using an improved Penman-Monteith equation. We aimed to provide critical information for water management improvement for wheat production facing climate change in the near future.

2. Materials and methods

2.1. Experiment site

Data for this study was from an open-air field experiment base simulating climate change conditions in a summer rice-winter wheat rotation system. Being initiated in 2010, the field experiment was located at Kangbo village (31°30′N, 120°33′E), Guli Township, Changshu Municipality in Jiangsu Province, China (Wang et al., 2016a). Being a typical rice/wheat producing area of China, the area is controlled by a subtropical monsoon climate. As illustrated in Fig. 1, total precipitation was 422.4 mm, 441.3 mm and 352.9 mm for the entire wheat growing season respectively of 2012–2013, 2013–2014 and 2014–2015 (Table 1). The soil is a cultivated Gleyic Stagnic Anthrosol formed on clayey lacustrine. The basic property of the topsoil at the start of the experiment was: soil pH (H_2O) 7.0, soil organic carbon 19.2 $g\,kg^{-1}$, total nitrogen 1.3 $g\,kg^{-1}$, total phosphorus 0.9 $g\,kg^{-1}$, total potassium 15.0 $g\,kg^{-1}$, and a bulk density of 1.2 $g\,cm^{-3}$. The soil texture is classified as loam with 33.8% sand, 38.6% silt and 27.6% clay.

2.2. Stimulated climate change condition

The climate change conditions simulated in the field experiment system were described in detail by Liu et al. (2015) and by Wang et al. (2016a). The treatments included ambient CO_2 concentration and temperature as control (CK), CO_2 enrichment up to 500 $\mu mol\,mol^{-1}$ (CE), canopy air warming by 2 °C over ambient (WA), and concurrent CO_2 enrichment and canopy air warming (CW). CO_2 enrichment and crop canopy air warming were sustained throughout the whole crop growing period. The treatments were conducted in separated octagonal rings, each having an area of 50 m^2 in the field. Each treatment was replicated in three rings with the same infrastructure and the rings arranged in a split row design. All the rings were buffered by the adjacent open fields about 28 m apart to avoid any cross-over effects from the treatments.

For the atmospheric CO_2 enrichment treatments (CE and CW), pure CO_2 gas (purity 99.99%) were supplied using a liquid CO_2