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# Aeration of different irrigation levels affects net global warming potential and carbon footprint for greenhouse tomato systems

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ABSTRACT

The study of aerated irrigation (AI) in conjunction with different irrigation levels on economic and environmental effects has important scientific significance for the selection of optimal irrigation and reasonable greenhouse management practices. In this paper, a two-year experiment was conducted to investigate tomato yield, water use efficiency (WUE), $CO_2$, $N_2O$, $CH_4$ emissions, net global warming potential (NGWP), and carbon footprint (CF) differences for a greenhouse tomato system in Northwestern China in 2016 and 2017. Based on the amount of irrigation needed to provide an adequate water supply (W), 60%W, 80%W and 100%W were set as the three irrigation levels, with two aeration regimes (aeration and control), totaling six treatments. Compared to the control, AI significantly increased tomato yield by 32.0%, WUE by 32.0% and CF by 24.0% on average ($p < 0.05$), but had no significant effect on soil $CO_2$, $N_2O$, $CH_4$ emissions and NGWP ($p > 0.05$). With respect to the treatment of 100%W, 80%W over the two years had no obvious effect on tomato yield, WUE and CF ($p > 0.05$), while 60%W reduced yield by 23.4% and CF by 32.6% but increased WUE by 35.1% significantly ($p < 0.05$). The effect of different irrigation levels on soil $CO_2$, $N_2O$ and $CH_4$ emissions, NGWP in 2017 and CF was not significant ($p > 0.05$). The main inputs in this arid and semi-arid region were electricity for irrigation and fertilizers, contributing 87.9%–92.9% of the total impact. Overall, the treatment of aerated full irrigation was suitable for crop production, water saving and carbon sequestration with WUE of 24.05 (in 2016) and 19.95 kg $m^{-3}$ (in 2017), a net greenhouse gas intensity of 0.103 (in 2016) and 0.086 (in 2017) t $t^{-1}$, and with a carbon footprint per tomato yield of 0.350 (in 2016) and 0.426 (in 2017) kg $CO_2$-eq $kg^{-1}$.

## 1. Introduction

Atmospheric $CO_2$, $N_2O$ and $CH_4$ are important greenhouse gases (GHGs), contributing significantly to global warming due to their long-lived cycle and unique radiative properties (IPCC, 2013). In total, the agricultural sector is responsible for emission of 1.4–1.6 Gt $CO_2$-eq $yr^{-1}$, accounting for 10–12% of the total global anthropogenic emissions (IPCC, 2014), and is the second largest source of emissions after fossil fuel consumption (Smith et al., 2008). Currently, China's agricultural area covers 11.6% of the total arable land (FAOSTAT, 2016). In 2007, agricultural production generated an estimated 686 Mt $CO_2$-eq (Chen and Zhang, 2010), corresponding to 9.2% of the national total anthropogenic GHG emissions. In 2014, tomato was one of the main commercial vegetables in China, with a planting area of 1.0 million hectares (FAOSTAT, 2016), though primarily cultivated in greenhouses (Yuan et al., 2001). However, massive use of nitrogen fertilization and irrigation are common practices in tomato production in China (Chen et al., 2004), resulting in many environmental problems, including GHG emissions. Continuous field measurements of $CO_2$, $N_2O$ and $CH_4$ emissions from tomato production systems are thus necessary to develop effective mitigation strategies for GHG emissions.

The calculation of carbon footprint (CF), which is an indicator for evaluating the contribution to global warming, has been widely applied to agricultural systems by accounting all GHG emissions directly and indirectly (Wiedmann and Minx, 2008; Finkbeiner, 2009). Knowing the sources of variability in CF accounting can provide insight for selection

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of low-carbon options, to identify the most effective carbon mitigation potential, and to choose key areas of research for technological improvements (Cheng et al., 2011; Pishgar-Komleh et al., 2017). Most studies regarding CF have thus far focused on paddy, maize and wheat production systems (Liu et al., 2016; Zhang et al., 2016), while research into China's greenhouse vegetable systems remains sparse. Hence, studies about CF are highly relevant for finding effective methods for reducing carbon loss in greenhouse tomato production systems in Northwestern China.

In recent years, aerated irrigation (AI), which is effective for overcoming rhizosphere hypoxia, has been studied and implemented in a variety of field soils for improving crop production, water use efficiency, fruit quality, $CO_2$ and $N_2O$ emissions (Abuarab et al., 2013; Ityel et al., 2014; Shahien et al., 2014; Hou et al., 2016; Li et al., 2016c). To the best of our knowledge, $CH_4$ emissions and variability in the full CF of greenhouse tomato production system has not been previously studied under AI treatment. Furthermore, there is still a dearth of research into the net global warming potential under AI. Water management, which affects soil aeration in turn, has been broadly studied for its influence on GHG emissions in paddy fields or in rice-wheat cropping systems (Liu et al., 2012; Xu et al., 2015). However, research about the effect of water management on GHG emissions, especially for deficit irrigation (DI) in greenhouse vegetable production systems is rare, and this lack of knowledge results in inaccuracies in the national inventory of GHG emissions for Chinese vegetable cropping systems. Although previous work has shown that full irrigation significantly increased soil $N_2O$ emissions compared to the deficit irrigation (Chen et al., 2018), there is still a gap in understanding with regard to the optimal irrigation mode that takes into account the co-benefits of crop production, water saving and GHG mitigation. Therefore, a combined study on the economic and environmental effects under AI and DI has important scientific significance for the selection of optimal irrigation and reasonable greenhouse management practices. Results of this work can also enhance understanding of the mitigation potential of a particular technology (such as AI and DI). The objectives of this study were to investigate the AI and DI effects on GHGs emissions, the CF of tomato production, yield and water use efficiency, and also to develop an irrigation mode targeted to reduce GHG emissions while promoting crop production.

## 2. Materials and methods

### 2.1. Study site

The experiment was implemented from March to July 2016 and from April to July 2017 in a solar greenhouse located N34°20′, E108°04′, at the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semi-arid Areas of Ministry of Education, Northwest A&F University, Yangling, Shaanxi Province, China. The site is in a semi-arid climate zone. Sunshine duration has a mean of 2163.8 h; and a mean frost-free period of 210 d. Lou soil is present in the experimental site with silt clay loam texture, and it has a field capacity of 32.1% (volumetric water content) with a bulk density of 1.35 g $cm^{-3}$. The depth of groundwater is at least 100 m below the surface. The properties of top-soil (0–20 cm) are as follows: organic matter, 13.71 g $kg^{-1}$; total N, 1.86 g $kg^{-1}$; total P, 1.40 g $kg^{-1}$; total K, 20.22 g $kg^{-1}$; and pH 7.65.

### 2.2. Experimental design

Tomato cultivar "Jinpeng No. 10" plants were grown in the greenhouse for the two-year experimental duration. According to local production practices, the tomato seedlings were transplanted from humus pots when they had 3 to 4 leaves and 1 heart. In 2016, tomatoes were transplanted on 28 March and harvested on 3 July. In 2017, the transplantation and harvest occurred on 6 April and 4 July, respectively.

Three irrigation levels were tested in this study: 60%W, 80%W, and 100%W. Here, W is the amount of irrigation needed to provide an adequate water, calculated following Eq. (1) (Hou et al., 2016):

$$W = k_{cp} \times E_{pan} \times A \quad (1)$$

where $k_{cp}$ is the crop-pan coefficient, being 1.0, $E_{pan}$ is the total evaporation quantity following the last irrigation event (mm), $A$ is the area controlled by one irrigation dripper in this experiment, being 0.14 $m^2$ (0.35 m × 0.4 m).

Each irrigation level contained aeration (AI) and non-aeration (control, CK). Hence, six treatments were included: aeration with 60% W (AI0.6), non-aeration with 60%W (CK0.6), aeration with 80%W (AI0.8), non-aeration with 80%W (CK0.8), aeration with 100%W (AI1.0) and non-aeration with 100%W (CK1.0). For each treatment, three plots having an area of 3.2 $m^2$ (4 m × 0.8 m) each, were established as three replicates. Therefore, a total of 18 plots were arranged using a randomized block design. A plastic film was installed at 100-cm depth between ridges to prevent lateral seepage of moisture. Eleven tomato plants were transplanted in each plot, spaced 35 cm apart. Throughout the whole growing period, all plots were covered with plastic film. Subsurface drip irrigation was buried to a depth of 15 cm with a dripper spacing of 35 cm A Mazzei air injector model 287 (a Venture, Mazzei Injector Company, LLC, Bakersfield, CA, USA), installed at the head of each irrigation pipe, was used for aeration with an inlet and outlet pressure of 0.1 Mpa and 0.02 Mpa, respectively. These air injectors were established to inject 17% air by volume of water (Zhu et al., 2016).

Irrigation water was supplied by a bucket connected to a pump (Fig. 1). Throughout the tomato growing period, irrigation was applied at an interval of 3–7 days. The total irrigation amount for the treatment with 100%W was 225.5 mm and 219.6 mm in 2016 and in 2017, respectively (Table 1). For each year, only basal fertilizer was applied, according to local farmers (Table 2), which was comprised of organic fertilizer ($N$-$P_2O_5$-$K_2O$ ≥10%, organic matters ≥45%) and compound fertilizer (total nutrient ≥45%, including N, $P_2O_5$ and $K_2O$ each at 15%). In addition, other agronomic managements, such as field preparation, planting, spraying, pruning, pollination and bactericide, were the same for all treatments as the local production practices.

### 2.3. Measurement index and methods

#### 2.3.1. Gas sampling and measurement

The $CO_2$, $N_2O$, and $CH_4$ fluxes were monitored through the static closed chamber method, following the procedure described by Hou et al. (2016) and Chen et al. (2018). The bases for the chambers, covering an area of 25 cm × 25 cm each, were placed, on the day of transplanting, in the middle of each plot between the two plants without covering crop vegetation, and remained there until tomato harvest (Fig. 1). The top edge of each base has a 3 cm-deep groove filled with water to seal the rim of the chamber. All chambers (25 cm × 25 cm × 25 cm) were made of 6-mm thick polyvinyl chloride material and wrapped with layers of sponge and aluminum foil (Chen et al., 2018). Each chamber was installed with an electric fan for gas mixing. Air temperature inside the chamber was recorded with a mercury thermometer (WNG-01, China) during the sampling period. Gas samples were taken between 10 to 11 a.m. at an interval of approximately 6 and 9 days during the early and late growing stages, respectively. Chamber air samples were collected followed 0, 10, 20, and 30 min using a 50-ml syringe through the three-way stopcock and a Teflon tube connected to the chamber after the chamber closure. A 30-ml air sample was drawn each time with the syringe. Gas samples in the syringes were analyzed within a few hours. Sample sets were accepted once they yielded a linear regression value of $r^2$ greater than 0.90.

Gas samples were analyzed for $CO_2$, $N_2O$, and $CH_4$ concentrations