ARTICLE IN PRESS

Agricultural Water Management xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Agricultural Water Management

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

Water use efficiency was improved at leaf and yield levels of tomato plants by continuous irrigation using semipermeable membrane

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ARTICLE INFO

Keywords:
Continuous irrigation
Processing tomato
Gas exchange
Stomatal limitation
Water use efficiency

ABSTRACT

Continuous irrigation (CI) is a newly developed irrigation technique that utilizes semipermeable membrane to release water into the plant root zone slowly and continuously. In order to investigate the effects of CI on plant gas exchange and water use efficiency (WUE) compared to conventional intermittent irrigation (II) under different soil water conditions, a field experiment was conducted on tomato plants during two growing seasons in the arid region of northwestern China. Gas exchange parameters were measured during fruit enlargement stage, which showed that the net photosynthesis rate of tomato leaf was similar between CI and II, while the stomatal conductance was significantly higher under CI for most measurements, resulting in significantly lower intrinsic WUE under CI compared to II. However, the non-stomatal limitations and lower vapor pressure deficit (leaf to air) caused significantly lower transpiration rate under CI, leading to slightly higher instantaneous WUE compared to II. Consequently, the total water consumption was reduced by CI. Moreover, CI also had significantly greater yield than II and therefore, CI improved WUE at both leaf and yield levels compared to II. CI can be used to reduce irrigation water use and increase WUE in crop production in northwestern China.

1. Introduction

Water scarcity is a major factor limiting agricultural production in arid and semiarid regions (Dadrasan et al., 2015). Water use efficiency (WUE) in agriculture, commonly defined as biological or economical yield produced per unit water consumed (Boyer, 1996; Molden et al., 2010), is described at leaf and yield levels in Table 1. Irrigation plays an important role in regulating plant growth and water use. The reduction of irrigation water and increase of WUE without compromising the yield is increasingly crucial for agricultural sustainability (Choudhary et al., 2010; Molden et al., 2010).

Continuous irrigation (CI) is a newly developed irrigation technique that utilizes a semipermeable membrane (SPM). CI delivers irrigation water directly into the plant root zone slowly, precisely and continuously (Fig. 1). Previous studies involving soil box experiments (Niu et al., 2013; Xue et al., 2013a; Zhang et al., 2012; Zhang et al., 2014) or numerical simulation (Xue et al., 2014; Zhang et al., 2015) showed that volume and flow rate of irrigation water under CI are proportional to the water head between inside and outside of the irrigation tapes. Compared to conventional drip irrigation methods, soil moisture distribution is more uniform within the wetting body under CI. Moreover, the ratio of length to width of the wetting body is close to one, thus water movement is mainly driven by water head and soil suction but not by gravity. The different soil wetting pattern under CI can affect plant water use processes. In intermittent irrigation, plants tend to maintain water status under fluctuating water supply through a regulation of water loss and water uptake (Cornic and Massacci, 1996; Sebastian et al., 2016). When plants uptake extra water due to the increase in soil water content (SWC) after precipitation or irrigation events, plant leaf transpiration rate (Tr) is elevated. Under CI, there is less fluctuation in soil moisture due to the continuous low flow rate released by the SPM. This means that the water logging that commonly occurs under II can be avoided. Many studies have found that CI using SPM increased crop yield, saved irrigation water, and increased WUE compared to intermittent irrigation (II) (He et al., 2012; Li et al., 2007; Tang et al., 2014; Xue et al., 2013b; Zhang et al., 2013). Xue et al. (2013b) measured diurnal variations of leaf Pn, Tr, and g_s under CI and II with similar irrigation volume during the vegetative growth stage of tomato plants in a greenhouse and found higher WUE at leaf level under CI. However, the mechanisms for the increased WUE under CI still remain unclear. Therefore, the aim of this study is to investigate whether CI improves WUE at leaf level by increasing stomatal conductance (g_s) and net photosynthesis rate (Pn) while decreasing Tr, and whether it also improves the WUE at yield level by reducing plant water consumption and increasing the yield.

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https://doi.org/10.1016/j.agwat.2018.02.007
Received 13 September 2017; Received in revised form 3 February 2018; Accepted 6 February 2018

Please cite this article as: Sun, Q., Agricultural Water Management (2018), https://doi.org/10.1016/j.agwat.2018.02.007

Nomenclature

Abbreviations

Ci	Intercellular CO_2 concentration
ET	Evapotranspiration
ET_0	Reference evapotranspiration
ET_r	Relative evapotranspiration, a ratio of ET to ET_0
g_s	Stomatal conductance
LS	Stomatal limitation
Pn	Net photosynthesis rate
SPM	Semipermeable membrane
SWC	Volumetric soil water content
Tr	Transpiration rate
VPD_L	Leaf to air vapor pressure deficit
WUE	Water use efficiency
WUE_{ET}	Crop water use efficiency
WUE_I	Irrigation water use efficiency
WUE_{in}	Leaf intrinsic water use efficiency
WUE_{ins}	Leaf instantaneous water use efficiency
WUE_{WP}	Normalized water use efficiency, a ratio of WUE_{ET} to ET_0

Treatments

CI	Continuous irrigation
C1	CI with relatively low system pressure (water head) in 2014
C2	CI with relatively high system pressure (water head) in 2014
CL	CI with relatively low system pressure (water head) in 2015
CH	CI with relatively high system pressure (water head) in 2015
II	Intermittent irrigation
I1	II with the same irrigation volume as C1 in 2014
I2	II with the same irrigation volume as C2 in 2014
IL	II with the same irrigation volume as CL in 2015
IH	II with the same irrigation volume as CH in 2015

2. Materials and methods

2.1. Experimental site and plant conditions

A field experiment was conducted at Shiyanghe Experimental Station of China Agricultural University from April to September 2014 and 2015. The experimental station is located in Wuwei city, Gansu province of northwestern China with typical inland arid desert climate (37°52′N, 102°51′E, at an altitude of 1851 m). The precipitation is approximately 164 mm/yr with pan evaporation of 2000 mm/yr, mean sunshine duration of 3000 h, mean annual temperature of 8.8 °C, and a frost-free period of over 150 d. The groundwater table is below 30 m.

The soil texture was sandy loam with organic matter content of 0.68–0.80%, field water capacity of 0.294 cm^3/cm^3 (measured with the method by Wilcox (1965)), wilting point of 0.100 cm^3/cm^3, and bulk density of 1.46–1.61 g/cm^3. A typical local variety of processing tomato (*Lycopersicon esculentum* Mill), Shijihongguan, was used in the experiment. The effective precipitation during the two growing seasons were 117.2 mm and 86.40 mm in 2014 and 2015, respectively. The cumulative Reference evapotranspiration (ET_0) during the two growing seasons were 409.49 mm and 486.80 mm, respectively.

Before transplanting, the soil was plowed by a rotary cultivator to a depth of 40 cm and fertilizers were uniformly spread throughout the soil within this layer. The quantity of N, P and K were 186.7, 169.0 and 103.8 kg/ha in the form of ammonium dihydrogen phosphate, urea and potassium phosphate. Tomato plants were transplanted into the field with plastic film mulch at the fifth leaf stage on 11th May 2014 and 5th May 2015. After transplanting, all treatments were irrigated sufficiently for plant growth. The plant density was six plants per m^2 for all the field plots. All the other field managements, such as weed control and pesticide, were same to the local managements.

2.2. Experimental treatments

Treatments included two irrigation methods, CI and II. Irrigation water for CI was stored in a tank with a diameter of 1.0 m and a volume of 0.8 m^3 per plot. The tank had a scale to record water level variation which was converted to daily irrigation volume. There were two irrigation volume treatments under CI controlled by a relatively low water head of 130–240 cm and a relatively high water head of 210–320 cm, abbreviated as C1 and C2 in 2014, CL and CH in 2015, respectively. Under II, plants were irrigated periodically, when CI treatments refilled their tanks, with exact the same volume of irrigation water, giving I1 and I2 in 2014 and IL (irrigated every 5.8 d on average) and IH (irrigated every 4.1 d on average) in 2014. Average irrigation water heads of CI treatments are shown in Table 3.

For CI, irrigation tapes with semipermeable membrane (Shenzhen Moistube Irrigation Co., Ltd, China) were used, while conventional subsurface drip irrigation (SDI) tapes (Dayu Irrigation Co., Ltd, China) were used in II treatments. The parameters of the two irrigation tapes are shown in Table 2. Since the flow rate of CI is proportional to water head, the flow rate was controlled by water head. The SPM is made into tape-shaped lateral providing uniform linear source irrigation by microporous inner layer (with a density of micropores higher than $10^5/cm^2$ and a diameter ranging from 10 nm to 900 nm).

Schematic of experimental plots are depicted in Fig. 2. There were three replicates per treatment, each separated by impermeable membrane buried vertically to a depth of 1.0 m. Each plot had 6 rows of tomato (row spacing and interplant spacings were 0.50 m and 0.35 m, respectively) with a SPM tape or SDI tape underneath each line. The plot areas were 36.25 m^2 and 49.50 m^2 in 2014 and 2015, respectively.

2.3. Measurements

2.3.1. Climate data, soil water content, reference evapotranspiration and crop water consumption

In both growing seasons, climate data were recorded every 15 mins by a weather station (Weather Hawk, Campbell Scientific, USA) located in the experimental site. ET_0 was estimated by Penman-Monteith equation (Allen, 2012). Volumetric soil water content (SWC) was measured using a DIVINER 2000 probe (Sentek Pty Ltd, Australia) in each field plot. The measurement was taken with 10 cm interval to 100 cm depth. FAO 56 (Allen, 2012) suggests Kc of tomato plants without any stress is around 1.05, therefore, Kc was determined for each treatment and showed that in 2015, CH and IH were under sufficient irrigation, while CL and IL insufficient; in 2014, I2 was relatively sufficiently irrigated while the rest of the treatments were insufficient to different extent (Table 3).

Actual crop water consumption within the growing seasons was estimated by soil water balance method:

$$ET = P + I - D - \triangle S \tag{1}$$

where ET is the actual crop water consumption (mm), P is effective precipitation (mm, defined as precipitation above 5 mm within a single rain event, calculated as actual precipitation deducted by 5 mm), I is the depth of applied irrigation water (mm), D is deep percolation or drainage below the root zone (mm), and $\triangle S$ is soil water depletion. The SWC at and below 60 cm deep remained relatively stable indicating no deep percolation during the experimental period.