Agricultural Water Management 177 (2016) 107–117

Contents lists available at ScienceDirect

Agricultural Water Management

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

Increasing the effective use of water in processing tomatoes through alternate furrow irrigation without a yield decrease

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ARTICLE INFO

Article history:
Received 29 April 2016
Received in revised form 25 June 2016
Accepted 2 July 2016

Keywords:
Partial root zone drying
Solanum lycopersicum L.
Leaf gas exchange
Water use efficiency

ABSTRACT

Surface irrigation represents >85% of irrigated agriculture worldwide. Partial root zone drying (PRD) is a technique for improving crop water productivity (WP), and in practice can be applied as alternate furrow irrigation (AFI). A series of research station and on-farm trials were conducted in two consecutive years and three soil types to evaluate processing tomato crop performance under AFI *vs* every furrow irrigation (EFI). Crop growth and leaf gas exchange, fruit biomass and quality, soil moisture and water applied were evaluated, and changes in irrigation WP (WP_i) determined in response to PRD. The AFI was consistent in maintaining fresh yields across cultivars and environmental conditions (i.e., years and soil textures) with at least 25% lower irrigation volumes than commonly applied under EFI. WP_i increased by >29% and maintained fruit quality under AFI. Canopy growth was slightly lower, and a tighter plant regulation of stomatal conductance (g_s) with only a small decrease in photosynthetic rates (P_n) was observed under AFI. Our results demonstrate that for California processing tomatoes AFI is effective in reducing agricultural water needs. Because of the extent of furrow irrigation worldwide, AFI can contribute to maintain highly productive agricultural land under production with lower water supply.

1. Introduction

Future constraints on water availability due to drought and increasing urban water demands require efficient irrigation strategies to reduce the amount of agricultural water use. Agricultural water consumption uses about 80% of the water supply. Globally, surface irrigation represents 86% of irrigated agriculture (FAO, 2015), and in many regions of the world is still the only feasible irrigation technique due to technical and financial constraints. Furrow irrigation is often considered to have low water use efficiency and may generate high volumes of runoff water that contribute to erosion and potential nutrient and pesticide pollution. By integrating plant physiological responses to soil water availability, furrow irrigation practices can potentially reduce water application without affecting crop productivity.

Partial root zone drying (PRD) is a technique for improving crop water productivity (WP; Perry, 2011) that maintains half of the root system under drying conditions while the other half has better access to soil water (Dry and Loveys, 1998; Kang and Zhang, 2004). Soil moisture availability is alternated between both sides of the root system. The regulation of transpiration, by partially closing the stomata, is considered to be the physiological mechanism to reduce plant water loss under PRD (Davies and Zhang, 1991; Kang and Zhang, 2004; Tahi et al., 2007), and this is probably modulated by signals between roots and shoot, such as an increase of abscisic acid (Dodd et al., 2006; Dry and Loveys, 1998) or other molecules (Chaves et al., 2007). Slight reductions in stomatal conductance have been shown to not affect carbon (C) assimilation while still diminishing transpiration and increasing plant water use efficiency. Studies show successful increases in WP with PRD without significant yield decreases in maize (Kang et al., 2000), vineyards (Dry et al., 2001), fruit trees (Hutton and Loveys, 2011) and horticultural and row crops (Kang et al., 2000; Kang and Zhang, 2004; Mingo et al., 2004). Under controlled conditions, PRD enhanced tomato root growth and stimulated plant physiological responses to drought stress-like conditions (Campos et al., 2009; Mingo et al., 2004; Tahi et al., 2007; Zegbe et al., 2004). Yet, other studies suggest that PRD may negatively affect yields (Casa and Rouphael, 2014; Kirda et al., 2007) or not be economically feasible (Sadras, 2009). More needs to be learned about how crop responses under field conditions may vary based on crop characteristics, irrigation management and specific environment conditions.

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http://dx.doi.org/10.1016/j.agwat.2016.07.006
0378-3774/

The WP of California processing tomatoes has increased in the past four decades and productivity has steadily improved at a 1.2% rate per year (USDA, 2009). Crop evapotranspiration has kept constant at an average of 65 cm (Hanson and May, 2005), but yields have increased more than 50% since the 1970s to currently over 100 Mg/ha (USDA, 2015). A comparison of 8 tomato cultivars released from 1936 to 2002 in California showed that a suite of morphological, physiological and phenological traits are responsible for improved yields and higher WP in newer cultivars (Barrios-Masias and Jackson, 2014). These include a decrease in canopy size due to a switch from indeterminate to determinate growth habit, and gains in leaf gas exchange, C assimilation and allocation (Barrios-Masias et al., 2014). Grandillo et al. (1999) evaluated the basis for yield gains observed between 1977 and 1994 and concluded that processing tomato genetic improvement and management practices contributed to this increase in similar proportions (i.e., ~50% each). These studies suggest that California processing tomato cultivars may possess high trait plasticity to respond to soil water availability, and thus new irrigation management strategies could further increase WP.

We hypothesized that water inputs can be reduced in processing tomatoes by applying the PRD technique under field conditions, due to better regulation of plant leaf gas exchange induced by pattern of soil water availability. Under commercial field conditions every furrow irrigation (EFI) is typically used, and with a simple change, alternate furrow irrigation (AFI), utilizes the PRD approach. The specific objectives were to: (1) evaluate if AFI could decrease water needs for processing tomatoes and increase irrigation WP (WP_i) without a yield decrease; and (2) assess if leaf gas exchange, plant canopy cover, C allocation to fruit and fruit quality were affected by AFI irrigation regime, which delivers less water. A series of research station and on-farm trials were conducted in two consecutive years to evaluate crop performance on soil types with varying water retention capacity. Crop growth and physiology, fruit biomass and quality, soil moisture and water applied were evaluated, and changes in WP_i determined in response to PRD.

2. Materials and methods

A total of 5 field trials were conducted in 2010 and 2011 to evaluate the effects of EFI (control) vs. AFI (less water using PRD) in processing tomato (*Solanum lycopersicum* L.). The trials were conducted in three different soil types and included three commercial processing tomato cultivars. To represent commercial production practices, each irrigator and field manager decided on the irrigation frequency and amount of water applied in every trial, using their typical practices for the EFI treatment. In all trials, the irrigation treatments were set up in strips of 6 contiguous planting beds, with the outermost bed on each side considered as buffers. Irrigation treatments started with the initial furrow irrigation event, and were applied for the same amount of time for EFI and AFI. The EFI strips had all furrows irrigated at each irrigation event, but the AFI strips received water on every other furrow, while the dry furrow received water in the next irrigation.

2.1. Station trial

This study was conducted in a 0.5-ha field at Campbell Research and Development Station in Davis, California (CA), USA, during 2010. Two highly-productive and widely planted processing tomato cultivars: 'AB2' (DeRuiter, St Louis, MO, USA) and 'CXD255' (Campbells, Davis, CA, USA) were established under the AFI and EFI treatments. A third cultivar ('SUN-6366'; Nunhems, Parma, ID, USA) was used as a buffer for the top and bottom part of the field, and only was evaluated during mechanical harvest. The station trial used identical practices as commercial processing tomato fields but allowed for precise irrigation management and even water distribution along the length of the furrows. The soil was mapped as a Reiff very fine sandy loam, a fine-silty, mixed, nonacid, thermic Typic Xerorthents with low water holding capacity (SSURGO 2016). Transplanting was on 18 May and harvest on 21 September 2010 (126 DAP; days after transplanting). The average solar radiation was 298 W m^{-2}, the minimum and maximum average temperatures were 11.6 °C and 29.6 °C, respectively, with a minimum of 2.2 °C and a maximum of 40.6 °C, and 9 mm of rainfall (CIMIS, 2015).

The field was tilled and beds were prepared (1.52 m from furrow to furrow) for transplanting in the spring. The field was divided in four irrigation strips of 6 beds each (24 beds total) grouped in two blocks. The irrigation treatments were randomly assigned to each irrigation strip within a block. In each irrigation strip, six plots were randomly assigned to the two cultivars (3 plots per cultivar per strip; 12 plots per cultivar and 24 plots total). Each plot was 9.1-m long and 9.1-m wide (6 contiguous beds). Planting density was a single row per bed with plant spacing of 0.36 m (25 plants per bed, and 150 plants (25 * 6 beds) in each plot). The field was machine transplanted on 18 May and sprinkler irrigated the following day to assure good plant establishment.

Irrigation treatments started 23 DAP and continued on average every 9 d for a total of 10 irrigations. Irrigation was applied using gated pipes to control water flow and even moisture distribution into the beds and furrows. The irrigation was controlled by damming the furrows to control even distribution along the length of the furrow and produce no run-off. Furrow inflow (m^3 s^{-1}) was measured for every furrow by weighing water flow samples for a set time period for all irrigations and all furrows. Total water applied (cm) was estimated based on the duration of each irrigation, and irrigation WP (WP_i) was calculated as harvestable fruit (see below) per amount of irrigation water used (Mg-FW cm-H_2O^{-1}).

Soil moisture was sampled before planting, at mid-season and after harvest (−7, 65 and 132 DAP, respectively). Samples were taken from the furrow and the planting bed (30 cm from the center; bed top width: 1 m) at three depths: 0–15, 15–30 and 30–75 cm. The first soil depth for the furrow position was considered to be 15–30 cm depth in relation to the top of the planting bed; thus, only two depths were taken from the furrow (15–30 cm and 30–75 cm). Soil sampling was done on both sides of a bed to account for soil moisture differences in the AFI treatment, and a composite sample was taken for gravimetric soil moisture (total of 120 composite samples in 24 plots). Soil moisture sampling to 300 cm depth was done before planting and after harvest (i.e., −5 and 137 DAP, respectively) for 7 depth increments (0–30 cm, and then at 45-cm increments below this).

Crop growth and plant performance were measured through the season in the two middle beds of each plot. Canopy measurements were done on average every 12 d with an infrared digital camera (Dycam, Woodland Hills, CA) mounted on an inverted 'L'-shaped pole to consistently cover a 3.6 m^2 area (i.e., 1.5 m of bed width by 2.4 m length along the bed). One picture was taken per plot and processed with Briv32 Version 1.27 software to obtain percent soil canopy cover (Barrios-Masias et al., 2014). Leaf gas exchange measurements were done with a field portable open flow infrared gas analyzer (IRGA; Model 6400, LI-COR Inc., Lincoln, NE, USA). Measurements were taken between 1000 and 1300 h with a 6 cm^2 chamber, with the CO_2 reference set at 400 μmol m^{-2} s^{-1}, and with saturating light using a LED source (PAR in: 2000 μmol m^{-2} s^{-1}). Six dates were sampled between 69 and 86 DAP (i.e., the stage of maximum plant growth and fruit set) using mature fully expanded leaves from the top of the canopy.

Biomass evaluations were conducted at the beginning of fruit set (65 DAP) and at harvest (126 DAP). At 65 DAP, four plants at each plot were cut at the base of the stem, separated into shoots and