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Improved water use efficiency and fruit quality of greenhouse crops under regulated deficit irrigation in northwest China

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ABSTRACT

Water limit is the major bottleneck that restrains sustainable development of agriculture in northwest China. In order to obtain higher water use efficiency (WUE) and improve fruit quality of greenhouse crops with less water, experiments with regulated deficit irrigation (RDI) on watermelon (*Citrullus vulgaris*; 2008–2010), hot pepper (*Capsicum annum L.*; 2011–2012) and tomato (*Solanumlycopersicum L.*; 2008–2013) in solar greenhouse were conducted in Shiyang River Basin of arid northwest China. Results showed that the feasible growth season of watermelon for high WUE and better fruit quality was in the winter-spring season with total irrigation amount of 114 mm. The specific irrigation water were 25, 12, 62 and 15 mm, respectively at seeding stage, plant-stem elongation stage, fruit bearing-expanding stage and fruit mature stage. It also showed that the positive relationship between hot pepper yield and seasonal evapotranspiration (ET) was fitted by linear model under drip irrigation, but exhibited an exponential relationship under furrow irrigation. The better RDI strategy for pepper to improve both WUE and fruit quality was maintaining soil water content at 70% of field capacity (θ_f) throughout the growth season except at the late fruit bearing and harvesting stage. At this stage, sufficient water (90% θ_f) should be applied. Results of tomato also suggested that the ventilation of greenhouse should be good around 1–3 pm in the local arid condition in northwest China. Mean values of Pn and Tr were decreased by 27.6% and 27.0% under irrigation quota of 214.2 mm, but leaf water use efficiency (WUE) significantly increased with comparison to quota of 260.8 mm. Moreover, the maximum values of yield and total water use efficiency (WUE_{ET}) of tomato were obtained at 89.5% and 77.0% of maximum ET, respectively. There are linear regression relationships between relative fruit quality parameters and relative ET, which provided a scientific basis for water-saving crop production in greenhouse. Application of such RDI strategy on greenhouse crops has great potential in saving water, maintaining economic yield and improving WUE and fruit quality.

1. Introduction

Globally, greenhouse with its advantages in high water productivity and high quality products by maintaining an optimum environment condition and prolonging the growing season (Harmanto et al., 2005), is developing rapidly to guarantee farmers' income as well as to save water. Greenhouse uses 15% cultivated land to provide jobs for 0.12 billion people and creates over 30% income increment. In China, the greenhouse has become one of the most active industries in agricultural structure (Du et al., 2015). Shiyang River basin is a typical region in northwest China with the planting area of greenhouse crops over 9.03×10^3 hm^2. During 2009–2011, the proportions of tomato, hot pepper and watermelon in solar greenhouse all over the basin were 26.1%, 25.0% and 10.5%, respectively. The total planting area of above three main crops is over 60%. The average yield of greenhouse crops has reached 93.2 t hm^{-2}, and the income brought to farmers was nearly 10–15 times than field crops. However, further increase of greenhouse production is restricted by various factors, among which water is the most important one (Ćosić et al., 2015), especially in northwest China where water resource is severely short (Wang et al., 2011; Zheng et al., 2013a).

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Surface irrigation is the main method adopted by farmers in greenhouse productions, especially in China. However, the irrigation management of crop grown in greenhouse is conducted according to farmers' experience, which may result in water wasting and poor fruit quality (Chen et al., 2013). Excessive utilization of irrigation water leads to over exploitation of groundwater resource and pollution of the environment (Du et al., 2014). Therefore an effective approach, i.e., regulated deficit irrigation (RDI), is applied in greenhouse to decrease the irrigation water demand, improve water use efficiency (WUE) and optimize crop yield and fruit quality (Ismail, 2010; Li et al., 2010; Ćosić et al., 2015). Moreover, drip irrigation system shows good potential in distribution uniformity and reducing soil evaporation (Karlberg et al., 2007). Before a decision is made to apply RDI, the exact timing of RDI and the degree of soil water deficit for different crop varieties and planting conditions still need to be investigated.

RDI has been successfully used on fruit trees (Yang et al., 2011; dos Santos et al., 2007) and cereals (Du et al., 2010; Li et al., 2015; Talebnejad and Sepaskhah, 2015; Igbadun et al., 2008). It was also used in greenhouse crops and tested that RDI improved crop water use efficiency and fruit quality (Sensoy et al., 2007; Wang et al., 2015, 2011; Ćosić et al., 2015; Zheng et al., 2013a,b; Ismail, 2010; Sezen et al., 2010). Previous studies showed that the improvement of WUE and quality of greenhouse crops by deficit irrigation are often paralleled with an undesirable yield penalties (Kuşçu et al., 2014a,b; Zheng et al., 2013a; Chen et al., 2013). Deficit irrigation applied near fruit ripening stage has the greatest positive influence on glucose and fructose accumulation in tomato fruits (Ripoll et al., 2014). Larger irrigation volumes have been proved to decrease melon fruit quality, especially total soluble solid (TSS) content (Sensoy et al., 2007). Patanè et al. (2011) reported that a good compromise between quantity and quality of tomato fruit was achieved when 50% reduction of evapotranspiration was applied for the whole growth season. Trade-offs between crop yield and quality might be achieved under controlled deficit irrigation, which provided that growers had access to quantitative information not only related to productivity but also to fruit quality. The positive relationships between tomato yield and seasonal ET were well fitted by linear models (Zheng et al., 2013a,b; Kuşçu et al., 2014b) as well as by curvilinear models (Patanè et al., 2011; Patanè and Cosentino, 2010). Accompanying with the positive relations between yield and seasonal irrigation amount, negative linear relationships were found between fruit quality parameters and seasonal ET (Ozbahce and Tari, 2010). Chen et al. (2014) reported that the relative values of tomato fruit quality parameters linearly increased with the drop of relative seasonal ET, mostly due to the enhancement by ET deficit at flowering and fruit development stage. Though RDI is rational in theory, it is still difficult for farmers to apply in the greenhouse crops. To obtain higher WUE and better fruit quality of greenhouse crops, precise regulating time and degree of deficit irrigation, quantitative relationships of WUE, fruit quality parameters and ET still need to be explored.

In this paper, field experiments were conducted on three typical crops of solar greenhouse, i.e., watermelon, hot pepper and tomato in northwest China during 2008–2013. The objective was to (1) assess the suitable regulated deficit irrigation strategies for high WUE and fruit quality of greenhouse crops; (2) propose scientific basis and useful guidelines to farmers on how to optimize water-saving irrigation strategy for sustainable greenhouse production.

2. Materials and methods

2.1. Experimental site

Field experiments of deficit irrigation were conducted on three typical crops, i.e., watermelon, pepper and tomato in the solar greenhouses at Shiyanghe Experimental Station for Water-saving Agriculture Ecology, China Agricultural University during 2008–2013. The station is located in Wuwei city, Gansu Province of northwest China (37°52′N, 102°50′E, altitude 1581 m), with pan evaporation of 2000 mm, annual precipitation of 164.4 mm and mean air temperature of 8.8 °C. The region has abundant light resources with mean sunshine duration of 3000 h and frost-free period of 150 days. The groundwater table is below 25 m, and the local crops are irrigated by well water with the electrical conductivity of 0.52 dSm^{-1}. Three adjacent solar greenhouses without extra heating system were used for all the experiments. The greenhouse was made of a steel frame, 76 m long and 8 m wide, covered with 0.2 mm thick polyethylene sheet on the surface, and the orientation is east-west with crop rows oriented in a north–south direction. A narrow ventilation system on the roof was used to control the inner temperature during the daytime. During the winter months, the woven straw mats were spread on the surface of the polyethylene sheet to maintain the interior temperature at night. There was little or no fallow period in greenhouses, but before next planting, plant debris was removed and the land was plowed, soil amendments added manure and fungicide. More details of the construction of the greenhouse were described by Qiu et al. (2011) and Chen et al. (2014). The soil is desert sandy loam and the field capacity ranged from 0.321 to 0.364 $cm^3\,cm^{-3}$. The average soil dry bulk density was 1.45–1.50 $g\,cm^{-3}$ in the 0–50 cm depth soil layer during the five years.

2.2. Experiment of regulated deficit irrigation on watermelon

Watermelon plants (cultivar Tulip beauty) were transplanted on September 23, 2011, February 26 and July 6, 2012 and uprooted on January 15, May 10, and September 13, 2012, respectively, in the winter season, the winter-spring season and the autumn season. The experiment was arranged in a randomized block design with 3 replications for a total of 9 plots during 3 seasons. Each plot was 33 m^2 and all covered by white polyethylene film with 0.005 mm thick and 1.2 m wide to reduce soil evaporation. Water was applied beneath the plastic film. Then watermelon seedlings were evenly transplanted along each edge of the raised bed (0.7 m wide and 0.2 m high) with density of 3.83 plant m^{-2}. The width of furrow was 0.45 m and planting distance was 0.5 m. The irrigation treatments consisted of three levels of irrigation amount through 3 seasons (Table 1). The control treatment (CK) was irrigated according to local operation. Regulated deficit irrigation treatments T1 and T2 was irrigated as designed upper and lower limitations and sole upper limitation through the growth stages, respectively. Fertilizing and insect control in all plots were the same for the 3 seasons.

Soil water content was measured by oven drying method in each plot, at 6-day intervals in 10 cm increments to a depth of 60 cm. There were 5 sampling points for each plot. Apart from the normal measurements, soil water content was also measured 1 day before and after each irrigation. The water amount in each irrigation event can be calculated as:

$$I = 10 \times \left(\theta - \theta_i\right) \times H \quad (1)$$

where I is the amount of irrigation water (mm); θ is the upper irrigation limitation ($cm^3\,cm^{-3}$); θ_i is the actual soil moisture content before irrigation ($cm^3\,cm^{-3}$); H is the planned moisture layer depth (watermelon, 60 cm).