Agricultural Water Management xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Agricultural Water Management

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

# Water use efficiency is improved by alternate partial root-zone irrigation of apple in arid northwest China

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ARTICLE INFO

*Article history:*
Received 13 January 2016
Received in revised form 6 May 2016
Accepted 9 May 2016
Available online xxx

*Keywords:*
Alternate partial root-zone irrigation
Apple tree
Evapotranspiration
Leaf area index
Yield
Water use efficiency

ABSTRACT

Apple is an important fruit tree in semiarid and arid areas, but increasing water scarcity limits apple productivity. Earlier studies have reported that alternate partial root-zone irrigation (APRI) can increase water use efficiency (WUE), but the effects of APRI with different irrigation frequencies on fruit yield and WUE are still unknown or contradictory. To close this knowledge gap, a two-year field experiment was conducted including two irrigation amounts (400 and 500 mm) and three irrigation methods (i.e. conventional irrigation with low frequency, APRI with low and high frequencies) in an apple orchard of the arid region of northwest China. Soil water content, sap flow, soil evaporation, leaf area index (LAI), fruit yield and components, and WUE on the basis of irrigation amount and tree evapotranspiration were evaluated. Results showed that (1) compared with low irrigation amount, high irrigation amount improved apple yield and significantly increased tree evapotranspiration and LAI; (2) in comparison of conventional irrigation, APRI could increase apple yield significantly and reduce tree evapotranspiration, so it enhanced WUE; (3) compared with low frequency, APRI with high frequency could improve apple yield and WUE. Our results demonstrated that alternate partial root-zone irrigation with high irrigation frequency has the potential to increase fruit yield and water use efficiency on the basis of tree evapotranspiration in arid northwest China.

## 1. Introduction

Apple is an important fruit tree in semiarid and arid areas of northwest China (Zhang et al., 2013), but conventional flood irrigation results in low water productivity (Kang et al., 2003a). To overcome the shortage of water resources in apple production, lots of water-saving techniques have been proposed worldwide, such as drip irrigation (Yang et al., 2013; Parvizi et al., 2014; Neilsen et al., 2015), deficit border irrigation (Laribi et al., 2013; Shan et al., 2013; Faci et al., 2014) and alternate partial root-zone irrigation (APRI). In APRI, only one part of the root-zone is alternately irrigated at varying frequency and APRI can reduce evapotranspiration without yield reduction (Kang et al., 1997, 2003a; Kang and Zhang, 2004). Fruit trees might be more suitable for the application of APRI technique because of their deeper root system and wide spacing (Du et al., 2005). In recent years, APRI has been investigated on apple (Talluto et al., 2008; Girona et al., 2010; Yang et al., 2011), grapevine (Dos Santos et al., 2003; Du et al., 2008; Intrigliolo and Castel, 2009), pear (Kang et al., 2003a,b) and peach (Vera et al., 2013).

Yield and WUE of fruit trees are positively affected during certain growth stages if irrigation amount of APRI satisfies the water requirement (Consoli et al., 2014), but yield and WUE would be probably influenced by water deficit at the fruit expanding and maturing stages. If such water deficit induces a decrease of transpiration rate below its maximum, it would be possible that production will be negatively affected because yield and WUE are depending on leaf photosynthesis, and amount and translocation of assimilation products (Kang and Zhang, 2004; Dodd et al., 2015).

Several studies have been carried out to find out the effects of APRI on yield and WUE. Compared with conventional irrigation, APRI increased the WUE of grapevine by 59%, but only reduced the yield by 14% (Loveys et al., 1997). Meanwhile, keeping the irrigation amount below 50% of sufficient irrigation, APRI reduced olive yield by 11% (Ghrab et al., 2013). In contrast, APRI significantly improved grapevine yield by 13% and WUE by 30% in the arid region of northwest China (Du et al., 2013). Above all, APRI has usually improved WUE, but no definite relationship existed was found between APRI and yield. However, it is still challenging to characterize how APRI affects yield for apple production.

Although there are many studies about the effects of APRI with different irrigation amounts on plant evapotranspiration, leaf area index, fruit yield and water use efficiency (Jensen et al., 2010;

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http://dx.doi.org/10.1016/j.agwat.2016.05.011
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Hutton and Loveys, 2011; Du et al., 2013; Ghrab et al., 2013; Zhao et al., 2015), fewer studies about the effects of APRI with different irrigation frequencies are investigated for apple production in arid region. Thus the objectives of this study were to (1) determine the effects of APRI on apple yield and WUE, and (2) compare low and high frequency APRI in terms of apple yield and WUE.

## 2. Materials and methods

### 2.1. Experimental site, meteorological data and soil water content

The experiments were conducted in an apple orchard at Shiyanghe Experimental Station of China Agricultural University, located in Gansu Province of northwest China (N37°52′, E102°50′, altitude 1581 m) during April to September in 2013 and 2014. The experimental site is in a typical continental temperate climate zone with an annual average sunshine duration of over 3000 h, frost free days of 150 d, temperature of 8 °C, annual accumulated effective temperature (>0 °C) of 3550 °C, precipitation of 164 mm, pan evaporation of about 2000 mm measured by a cylinder Class A evaporation pan with 120.7 cm in diameter and 25.0 cm in depth, and groundwater table depth of 25 m. The soil texture is light sandy loam, with bulk density of 1.46 $g\,cm^{-3}$ and mean field capacity of 0.30 $cm^3\,cm^{-3}$ at 0–1.6 m layer (Liu et al., 2012).

Net radiation, temperature, relative humidity and wind speed at the height of 4.0 m and soil heat flux at the depth of 0.1 m were automatically recorded by meteorological monitoring system (Jauntering, Taiwan) located in the center of the experimental site (Fig. 1). Meteorological parameters at different growth stages of apple tree during 2013 and 2014 are shown in Table 1. According to empirical frequency calculation of long-term precipitation, 2013 was a dry year ($p = 75\%$) and 2014 was a wet year ($p = 25\%$).

The variations of environmental factors were small during the whole growth season across the experimental years for net radiation, air temperature, relative humidity and reference evapotranspiration (Table 1). However, the variation of precipitation was large during the bud development and flowering, and fruit expanding stages across the experimental years. The total precipitation was 80 mm in 2013 and 242 mm in 2014. Rainfall mostly fell during the fruit expanding stage and less during the other three stages (Table 1).

Soil water content of each subplot was monitored every 5–7 d by Diviner 2000 system (Sentek Pty Ltd., Australia) at 0.1 m intervals of the vertical soil layer. In each subplot, four PVC access tubes with the depth of 160 cm were installed at the distances of 1.0 m and 1.5 m from the tree trunk both south and north sides, as shown in Fig. 1. Additionally, gravimetric soil water content was measured by the oven-drying method and calibrated the data from Diviner 2000 system (Sentek Pty Ltd., Australia) at each growth stage. Two representative trees were selected for the measurements in each treatment. Seasonal variations of soil water content for all the treatments in 2013 and 2014 are shown in Fig. 2. If the soil water content was lower than 50–55% of the field capacity (0.150–0.165 $cm^3\,cm^{-3}$), it would cause water stress to tree growth and final yield.

### 2.2. Experimental design, selection of apple tree and field management

A field of about 0.5 ha (68 × 66 $m^2$) including 170 trees was chosen for this experiment where apple trees (*Malus domestica Borkh.* cv Golden Delicious) were planted in 1981, with a row spacing of 6 m and a plant spacing of 4 m (Fig. 1). The apple trees are arranged in east-west direction. To avoid the damage of other trees and reduce workloads, only 18 representative trees were selected for this study with similar trunk diameter and bark depth, and located in the middle of the experimental site. The radius of sapwood and heartwood were measured for all treatments (Table 2). Those 18 trees were separated in three blocks as three replicates (Fig. 1).

For two seasons, the field experiment had six treatments (two irrigation amounts and three irrigation methods) and was arranged in a randomized block design, and replicated three times. Two irrigation amounts were 400 and 500 mm. According to the conventional border irrigation amount 500 mm, which accounted for 80% of the average evapotranspiration (Liu et al., 2012), 400 mm was set up for water deficit in this experiment. Three irrigation methods included (1) conventional irrigation with low frequency (CI), irrigation water was uniformly supplied to the isolated subplot (9 $m^2$, 3 m × 3 m) surrounding the tree with total of 4 times during the whole growth season; (2) APRI with high frequency ($PRI_H$), irrigation water was alternately supplied to two parts of isolated subplot surrounding the tree with total of 8 times; (3) APRI with low frequency ($PRI_L$), irrigation water was alternately supplied to two parts of isolated subplot surrounding the tree with total of 4 times. Four times was the conventional border irrigation frequency as a control and 8 times was set up for high frequency as a contrast. The irrigation water was supplied to each individual subplot by irrigation pipelines from a well near the experimental site. The pipelines were connected with a water meter to monitor the water inflow. Irrigation date, amount and frequency are shown in Table 3.

In order to minimize horizontal water and nutrient flow between neighboring subplots, each subplot was isolated by impermeable film with a depth of 1.5 m, 3 m in width and 3 m in length. The tree was located in the center of the isolated subplot (Fig. 1). There was a ridge of 0.3 m high above the surrounding boundary to avoid water flux in and out of the isolated subplot. In addition, the subplot for APRI treatment was divided into two equal parts for alternating irrigation to keep one part wet and the other dry, and the dividing line is in east-west direction. Impermeable film was buried under the depth of 0.5 m and there was a ridge of 0.3 m high above the dividing line to separate water from the other side. Each year the trees were fertilized with 800 $kg\,ha^{-1}$ $CO(NH_2)_2$, 200 $kg\,ha^{-1}$ $P_2O_5$ and 150 $kg\,ha^{-1}$ $K_2O$, and had similar agronomic management in the orchard.

### 2.3. Sampling and measurements

#### 2.3.1. Fruit number and yield

Fruit number and yield per tree were calculated and weighted after picking in 21 September, 2013 and 26 September, 2014, respectively.

#### 2.3.2. Leaf area index

The canopy hemispherical photographs of apple trees were taken using Winscanopy canopy analysis system (Winscanopy 2006a, Regent, Quebec, Canada). The setting mode and the types of lens in camera were same as the method of Liu et al. (2013). Measurements were done after sunset or before sunrise to reduce the effects of sunlight on measurement every 5–7 d. Two representative trees were selected for the measurements in each treatment due to time consumption and workloads. LAI was calculated by Winscanopy 2006a (Regent Instruments, Ste-Foy, Quebec).

#### 2.3.3. Sap flow

Sap flow of apple trees was monitored by the sap flow sensors of compensation heat pulse (Model SF100, Greenspan Technology Pty Ltd., Warwick, Australia). Two probes were installed on the east-west side of the trunk, and the depths were 1 cm and 1.5 cm in the xylem, respectively. Sap flow sensors were installed in the trunk at 20 cm above the ground (Liu et al., 2012), and the probes were wrapped with foil to reduce the effects of environmental heat. Time

Please cite this article in press as: Du, S., et al., Water use efficiency is improved by alternate partial root-zone irrigation of apple in arid northwest China. Agric. Water Manage. (2016), http://dx.doi.org/10.1016/j.agwat.2016.05.011