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Signal intensity based on maximum daily stem shrinkage can reflect the water status of apple trees under alternate partial root-zone irrigation

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ABSTRACT

Signal intensity (*SI*) and maximum daily stem shrinkage (*MDS*) are indicators of the water status and irrigation schedule of fruit trees under conventional irrigation (CI). However, whether *SI* can reflect the water status of fruit trees under alternate partial root-zone irrigation (APRI) has rarely been reported. Field experiments were conducted on apple trees over two years with two irrigation methods (CI and APRI) and two irrigation amounts (400 mm and 500 mm) in an arid area. The followings were measured over the whole growth season: *MDS*, sap flow (*SF*), air temperature, net radiation, vapor pressure deficit, reference evapotranspiration, soil water content, midday stem water potential and predawn leaf water potential. The signal intensities based on *MDS* (SI_{MDS}) and sap flow (SI_{SF}) were calculated. The results show: first, *MDS* was significantly higher under CI at 400 mm than under APRI at 400 mm, while no difference was found between the two irrigation methods at 500 mm. *MDS* was significantly positively correlated with meteorological factors, while SI_{MDS} and SI_{SF} were not. Second, SI_{MDS} was significantly lower under APRI than under CI, while no difference was found in SI_{SF} between the two irrigation methods. Third, in contrast to SI_{SF}, SI_{MDS} was significantly correlated with soil water content as well as with midday stem water potential and predawn leaf water potential under APRI. These results show that the signal intensity based on maximum daily stem shrinkage accurately indicates the water status of apple trees under alternate partial root-zone irrigation in an arid apple production area.

1. Introduction

Water resources are limited in arid areas, and thus scientific analysis of water management which can provide a fast and accurate estimate of water status is the basis for efficient water use and the subsequent high yield of fruit trees (Fernández and Cuevas, 2010; Conesa et al., 2016a; Kang et al., 2017). Stem and leaf water potentials are often used to estimate the water status of fruit trees (Ruiz-Sánchez et al., 2004; Conesa et al., 2016b; Mirás-Avalos et al., 2016; Parvizi et al., 2016), but the measurement is time-consuming and laborious (Fernández and Cuevas, 2010; Liu et al., 2011). Recent studies have focused on the evaluation of maximum daily stem shrinkage (*MDS*) and sap flow (*SF*) to quickly and accurately diagnose water status and schedule conventional irrigation (Cocozza et al., 2015; Robles et al., 2016).

Previous studies have shown that *MDS* can reflect the cycles of cell water absorption and dehydration, as well as thermal expansion and contraction (Daudet et al., 2005; Ortuño et al., 2010), while sap flow can indicate the transpiration of fruit trees (Intrigliolo and Castel, 2006; Cocozza et al., 2015). However, *MDS* and sap flow are significantly affected by meteorological factors which, if not recognized, can lead to an inaccurate estimate of water status, and so result in under-irrigation (Moriana et al., 2011; Corell et al., 2013). For instance, in apple trees, *MDS* and sap flow are significantly correlated with vapor pressure deficit, air temperature, net radiation and reference evapotranspiration (Liu et al., 2011, 2012). In addition, without considering the evaporative demand, the absolute *MDS* value may not accurately represent tree water status (Ortuño et al., 2010). At a higher evaporative demand under well-watered conditions, *MDS* might be the same as it would be at a lower evaporative demand under water-stressed conditions (Fernández and

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Cuevas, 2010). It has been suggested that the use of signal intensity, which normalizes the absolute values with respect to values in non-limiting soil water conditions, will lead to more effective irrigation scheduling (Ortuño et al., 2010).

Signal intensity (SI_{MDS} and SI_{SF}, the ratios of measured MDS and sap flow to their respective values obtained under full irrigation), can be used to eliminate sources of error and to reduce the impacts of meteorological factors on data obtained under conventional irrigation (De la Rosa et al., 2014, 2015). Previous studies have shown that irrigation can be scheduled based on SI_{MDS} under conventional irrigation (Goldhamer and Fereres, 2004). For example, when compared with SI_{SF}, SI_{MDS} was more sensitive to water variation in peach trees, and the irrigation schedule based on SI_{MDS} was more precise (Conejero et al., 2007a,b). Another study showed that SI_{MDS} could be used to estimate the water status of almond trees under deficit irrigation (Puerto et al., 2013). However, contradictory results have shown neither SI_{MDS} nor SI_{SF} was suitable for evaluating the water status of olive trees under deficit irrigation (Fernández et al., 2011a). Whether SI_{MDS} and SI_{SF} are suitable for the development of irrigation protocols under alternate partial root-zone irrigation in arid areas has been little studied, and merits further exploration.

The arid area in northwest China is beneficial to apple production because of abundant sunlight, larger temperature differences between day and night and the dry climate. It produces high quality fruit with high yields. With increasing market demand and expanded planting areas, water shortage has become the most significant limiting factor for apple production. Improving effective water utilization is a necessity for the sustainable development of local agriculture (Kang et al., 2017). Alternate partial root-zone irrigation (APRI) is an innovative water-saving technology that can regulate stomatal aperture and reduce luxury transpiration by alternately wetting the root area and allowing it to dry before subsequent wetting (Kang et al., 1997; Kang and Zhang, 2004). It has recently been shown that APRI improves apple yield and water use efficiency, while it reduces evapotranspiration and leaf area index when compared to conventional irrigation (Du et al., 2017). However, the determination of the water status of apple trees under APRI is complex, and thus it is necessary to find a convenient and reliable indicator of water status which can then be used to guide water management in apple orchards.

To this end, a two-year field experiment was carried out in an apple orchard of arid northwest China. The objectives of this study are: (1) to compare the differences in MDS between conventional irrigation (CI) and APRI with irrigation amounts of 400 mm and 500 mm; (2) to determine the effects of CI and APRI on signal intensities based on MDS and sap flow; (3) to assess the feasibility of using signal intensity based on MDS to indicate the water status of apple trees in order to guide the application of APRI.

2. Materials and methods

2.1. Experimental site and meteorological parameters

Field experiments were carried out during 2013 and 2014 in an apple orchard that is located at Shiyanghe Experimental Station of China Agricultural University in Gansu Province (N37°52′, E102°50′, altitude 1581 m). The experimental site is in a continental temperate climate area. Sunlight is abundant with annual sunshine duration of >3000 h. The annual average temperature is 8 °C, and the annual accumulated temperature (>0 °C) is >3550 °C. Water is a limited resource with annual average precipitation of 164 mm, pan evaporation of ~2000 mm and the mean depth to the surface of the groundwater table is >25 m below the land surface (Liu et al., 2011). The soil classification at the experimental site is Siltigic-Orthic Anthrosols with a light sandy loam. At field capacity, the mean volumetric soil water content is 0.30 cm^3 cm^{-3} for the 0–1.6 m layer, and the mean bulk density is 1.46 g cm^{-3} (Liu et al., 2012). The meteorological parameters at each growth stage and over the whole growth season of the apple trees are summarized in Table 1.

2.2. Experimental design and field management

This field experiment was arranged as a randomized block design with three replicates. It consisted of four treatments, each including two factors (irrigation method and irrigation amount). The four treatments were: (1) conventional irrigation (CI) with 400 mm; (2) CI with 500 mm; (3) alternate partial root-zone irrigation (APRI) with 400 mm; and (4) APRI with 500 mm. According to previous investigations of local farming practices (Liu et al., 2011, 2012), 500 mm was selected to be the conventional border irrigation amount, while 400 mm was chosen as the deficit irrigation amount. The total irrigation amount was administered at four intervals (100 mm or 125 mm each) during the whole growth season. For CI, the water was supplied uniformly within the subplot through irrigation pipelines which were connected to a water meter to monitor the irrigation amount. For APRI, the same amount of water was alternately given to one half of the subplot and then to the other half at the next irrigation event through irrigation pipelines (Fig. 1). All the plots were irrigated on 26 April, 31 May, 27 June and 1 August in 2013, and on 25 April, 5 June, 13 July and 7 August in 2014.

To complete this experiment, a field of ~0.5 ha (68 m × 66 m) containing 170 trees was selected. Apple trees (*Malus domestica Borkh*. cv Golden Delicious) had been grown in the field since 1981 with row spacing of 6.0 m and plant spacing of 4.0 m. There were three separate replicate blocks. Each block was composed of 15 trees in three rows with five trees in each row. Four trees in each block were selected as experimental trees. They were similar in trunk diameter, bark depth, and radii of sapwood and heartwood (Du et al., 2017). Impermeable isolation film of width 3.0 m and

Table 1
Daily average maximum air temperature (T_{max}), net radiation (R_n), vapor pressure deficit (VPD) and reference evapotranspiration (ET_0), and accumulated precipitation (P) at different growth stages of the apple trees in 2013 and 2014.

Year	Growth stage	T_{max} (°C)	R_n (W m^{-2})	VPD (kPa)	ET_0 (mm d^{-1})	P (mm)
2013	Bud development and flowering (4.5–5.14)	23.7	123.9	1.5	3.9	6.0
	Leaf expansion (5.15–6.20)	26.0	125.5	1.6	3.8	18.2
	Fruit expanding (6.21–9.1)	28.6	122.9	1.4	3.5	40.4
	Fruit maturing (9.2–9.22)	25.1	96.9	1.2	2.7	15.8
	Whole growth season (4.5–9.22)	26.6	120.3	1.5	3.5	80.4
2014	Bud development and flowering (4.9–5.20)	20.1	119.0	1.1	3.4	55.8
	Leaf expansion (5.21–6.30)	27.0	137.7	1.5	4.2	22.6
	Fruit expanding (7.1–9.5)	27.5	133.7	1.3	3.7	152.2
	Fruit maturing (9.6–9.27)	22.5	85.1	0.9	2.2	11.2
	Whole growth season (4.9–9.27)	25.0	125.8	1.3	3.6	241.8