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Response of fruit yield, fruit quality, and water use efficiency to water deficits for apple trees under surge-root irrigation in the Loess Plateau of China

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ABSTRACT

This study investigated the response of the fruit quality, fruit yield, and water use efficiency (WUE) to regulated deficit irrigation (RDI) during the different growth stages of apple trees (*Malus pumila Mill*) in the Loess Plateau of northern China. Different water deficit treatments were applied in 2016 and 2017 on a field planted with 5-year-old apple trees. The treatments included low (L), moderate (M), and severe (S) water deficit treatments during the bud burst to leafing (I), flowering to fruit set (II), and fruit growth (III) stages. Compared with full irrigation (FI), water deficit treatment during the different growth stages had significant effects on the fruit quality, fruit yield, and WUE of the apple trees. The L and M water deficit treatments during stage III significantly reduced the apple yield by 10.89% and 13.46% in 2016 and 3.66% and 10.10% in 2017, respectively. A water deficit during stage III decreased the single fruit weight, excellent-fruit percentage, and fruit water content by 2.79%–11.31%, 15.24%–20.36%, and 4.26%–10.07%, respectively, and increased fruit firmness, soluble solid content, and soluble reducing sugar content by 12.70%–21.31%, 13.83%–33.60%, and 10.13%–21.48%, respectively. The L and M water deficit treatments applied during stage I resulted in apple quality and yield that were similar to those resulting from the FI treatment, but the WUE was significantly higher in the L and M water deficit treatments than in the FI treatment. The optimal period for water deficit treatment is stage II, during which the highest yield and WUE were found. The L and M treatments during stage II increased the fruit yield by 13.93% and 13.28% in 2016 and 17.94% and 17.13% in 2017, respectively. The WUE of the apple trees was higher with the I I-L and I I-M treatments (greater than 7 kg m^{-3}) than with other treatments. In addition, water deficit treatment during stage II caused a slight increase in fruit firmness and a slight decrease in fruit water content, which produces apples suitable for storage. Single fruit weight, excellent-fruit percentage, and soluble solid and soluble reducing sugar content were significantly improved, making the apples sweeter; thus, a water deficit during stage II had a significant positive effect on apple quality, with the I I-M treatment being optimal and the II-L treatment being second best. The optimal water deficit treatment of the II-M treatment enhances the fruit quality, yield, and WUE of apple trees in water-scarce environments.

1. Introduction

Drought and soil erosion in the Loess Plateau of China have led to a severe water shortage in the region. In recent years, the local apple industry has expanded rapidly, with more than 628,600 ha being cultivated for this purpose, accounting for a quarter of China's apple yield (Shaanxi Provincial Bureau of Statistics, 2016). The water demand of apple trees is high, which seriously affects the distribution of water resources in the region, increasing the difference between water supply and demand. The water shortage is severely restricting the further development of the apple industry in the region (Song et al., 2018). Therefore, how the water use efficiency (WUE) can be improved and irrigation water rationally distributed in the region are crucial research questions.

To improve the WUE, scholars have proposed advanced water-saving irrigation techniques, such as sprinkler irrigation, drip irrigation, intermittent irrigation, film hole irrigation, and surge-root irrigation (SRI). SRI is a new technology of microirrigation and is similar to subsurface drip irrigation. In SRI, the WUE is improved because irrigation water is directly transported to the roots of the crop rather than

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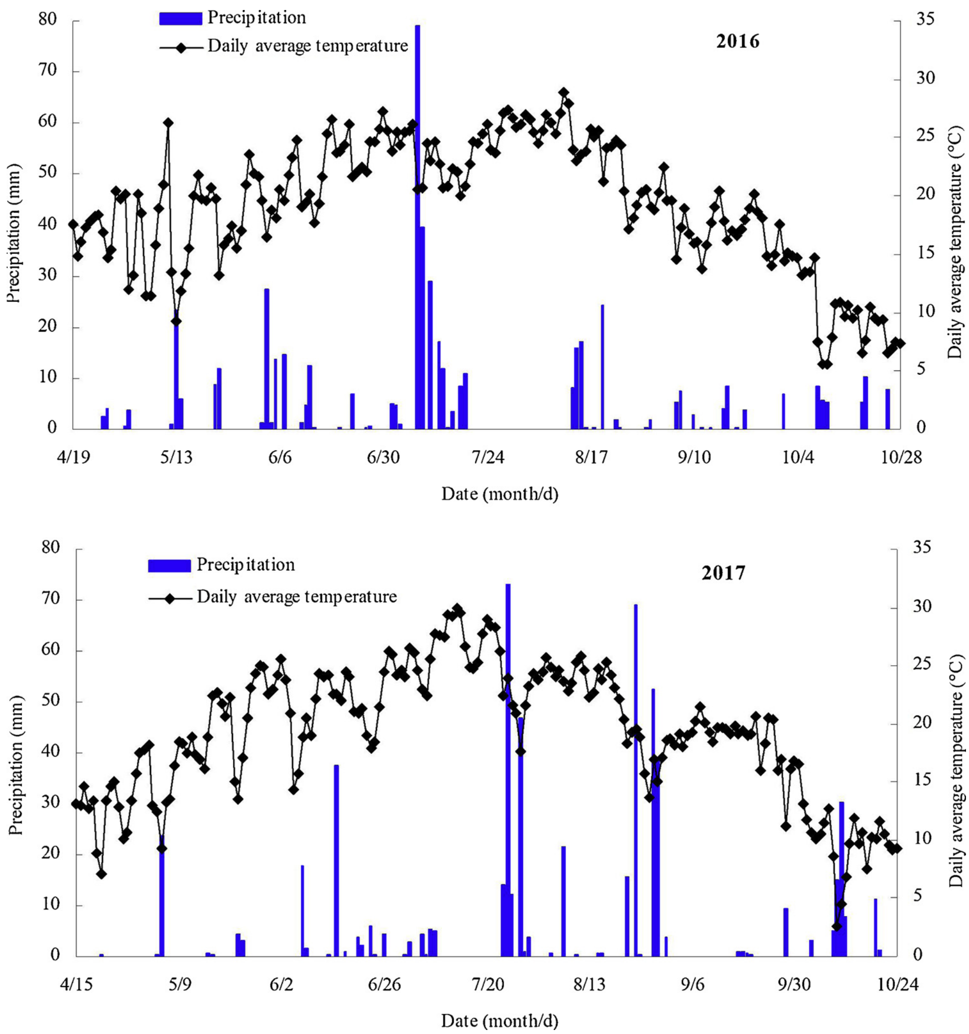

Fig. 1. Daily rainfall and average temperature during the 2016 and 2017 apple growing seasons.

to the soil, which reduces the amount of water evaporation, and irrigation water is not affected by the wind (Dai et al., 2019; Wu et al., 2010). The SRI approach is currently evolving. Scholars have improved the material and flow channel of the SRI emitter (Zhang et al., 2007, 2017), which has improved the crack resistance of the emitter and casing pipe and has solved the problem of silt blockage; furthermore, irrigation uniformity and anticlogging ability have been improved, making SRI especially suitable for the irrigation of economically important trees. Wu et al. (2010) discovered that the greatest improvements to the yield and quality of jujube trees were obtained using SRI compared with using tube or drip irrigation. Among the three irrigation methods, SRI resulted in the highest net income ratio, which was 235.0% compared with the ratio for no irrigation (NI).

Scholars have proposed the regulated deficit irrigation (RDI) method for most appropriately distributing limited irrigation water (Chalmers and Ende, 1975); this method uses the physiological function of crops to save water by formulating a rational irrigation system and optimizing the irrigation time and quota of the limited irrigation water during the crops' entire growth period. RDI controls crop vegetative growth and leaf water potential by regulating soil moisture, and stomatal opening can be regulated using leaf water potential, which has a strong effect on photosynthesis and water use of crops (Fábio et al., 2002). Numerous field experiments have demonstrated that crops have certain adaptability to water deficits; a moderate water deficit may not considerably reduce crop yield (Cui et al., 2008). Crop growth is inhibited when crops have been subjected to a short-term water deficit, but after the water supply is restored, crops overcompensate (Kou et al., 2014). RDI employs the physiological water-saving characteristics and drought-resistance ability of crops to save water, increase yield, improve crop quality, and obtain the maximum benefits for a limited water input.

Since the theory of RDI was proposed, scholars (Ali et al., 2018; Candogan and Yazgan, 2016; Chaichi et al., 2016; Sampathkumar et al., 2013; Singh et al., 2010) have verified its effects on the growth and yield of wheat, corn, soybean, and cotton from different perspectives. In addition, many studies have assessed the growth of fruit trees under RDI, mainly concentrating on the physiological and biochemical reactions in dryland fruit trees such as apple (Chenafi et al., 2016), peach (Yuan et al., 2009), pear (Cheng et al., 2012), grape (Faci et al., 2014), and jujube (Qiang et al., 2015) crops. Research has shown that for fruit trees, moderate water stress inhibits overgrowth by balancing vegetative with reproductive growth and has little effect on the normal growth and development of fruits, which achieves the purpose of water saving while producing a stable yield and high-quality fruits.

Although much research has been conducted on RDI, there is little research on the RDI of apple trees under the special irrigation method of SRI in the Loess Plateau of China. The water consumption of apple trees is higher than that of ordinary crops, and the water demand during the different growth periods is inflexible (Chenafi et al., 2016; Song et al., 2018). The main irrigation method employed in this region is flood irrigation, and the WUE is low (Kou et al., 2014). An appropriate irrigation system is urgently required to improve the WUE of apple trees in this region. Therefore, the objectives of this study were to (i) determine the effects of RDI on the fruit quality, fruit yield, and WUE of apple trees and (ii) determine the optimal water deficit period of apple trees to provide a scientific basis for water management and the precise irrigation of apple trees.

2. Material and methods

2.1. Experimental location and growth conditions

Field experiments were conducted during the apple growing seasons (April–November) of 2016 and 2017. The experiments were performed at a modern agriculture apple demonstration orchard with micro-irrigation that is located in Qianshuigou Village, Zizhou County, Yulin City, Shaanxi Province, northwest China (37°27′N, 110°2′E, altitude: 1020 m). This area is a typical hilly–gully region of the Loess Plateau and has a semiarid climate. The soil of the experimental location is classified as sandy loam with favorable hydraulic properties (Gao et al., 2018). Total precipitation over the entire growth stage of the apple trees was 441.7 and 475.0 mm in 2016 and 2017, respectively (Fig. 1). The highest daily mean temperatures in 2016 and 2017 were 28.9 and 30.0 °C, respectively. The daily mean temperature was > 15 °C for 151 days in 2016 and 148 days in 2017 (Fig. 1). The average number of annual sunshine hours was 2632.9 h. Moreover, in the experimental location, groundwater was more than 50 m below the ground level, with no replenishment effect on the designed soil profile. Table 1 presents the basic properties of the soil profile at the beginning of the study.

2.2. Experimental design

Five-year-old apple trees (*Malus pumila Mill*) were selected as the experimental trees. The selected trees were healthy and showed uniform growth. The trees were planted with 2-m within-row spacing and 3-m inter-row spacing (1665 plants ha^{-1}); their height was 2.5–3.0 m. More than 90% of the trees' absorbent roots (< 2 mm in diameter) were located at a depth of 80 cm (Song et al., 2018); therefore, the depth of soil water content (SWC) controlled in this study was 80 cm. The layout of the test irrigation system is illustrated in Fig. 2.

The entire growing season of the apple trees was divided into the bud burst to leafing stage (stage I, mid-April–mid-May), flowering to fruit set stage (stage II, late May–mid-June), fruit growth stage (stage III, late June–late September), and fruit maturation stage (stage IV, early October–late October). The divisions of the season into stages and the effective rainfall in each stage in 2016 and 2017 are presented in Table 2.

Apple trees are tolerant to drought, and suitable SWC is 40%θ_f to 85%θ_f (where θ_f is the field capacity). Therefore, the experimental treatments were low (L), moderate (M), and severe (S) water deficit treatments with three irrigation levels in each growing stage. The three irrigation levels applied were defined based on SWC: L: 70%θ_f –85%θ_f, M: 55%θ_f –70%θ_f, and S: 40%θ_f –55%θ_f. When SWC was below the lower limit, irrigation was performed until SWC reached its upper limit. Because of the considerable rainfall in 2016 and 2017, SWC did not decrease to 40%θ_f –55%θ_f during stages II or III; therefore, the S water deficit treatment was not conducted in stages II and III. Additionally, the physiological activity of the trees during stage IV was slow because of the rapidly decreasing temperature at the end of the growing season, so no irrigated, that is no water deficit in stage IV also. Full irrigation (FI, 85%θ_f –100%θ_f) and NI treatments were used as controls. Overall, nine treatments were designed and applied. Each treatment was applied to three apple trees, and 81 trees in total were arranged in a strip-plot design according to completely randomized blocks with three replications. The 81 apple trees selected were healthy, vigorous, and uniformly sized, and isolated trees were set between each treatment. Standard agronomic measures such as fertilization, trimming, girdling, insecticide spraying, and weed control were the same for all trees. The scheme of RDI is displayed in Table 3 for the different growth stages of the apple trees in the field experiment.

Irrigation water was obtained from a deep well that contained water of suitable quality for apple growth. A water meter (nominal diameter: 25 mm) was used to control the irrigation amount for each treatment. In early April, 0.6 kg $plant^{-1}$ of P_2O_5, 0.5 kg $plant^{-1}$ of K_2O, and 1 kg $plant^{-1}$ of organic fertilizer (sheep manure) were used as base fertilizer at 30 cm from the main trunk of the fruit tree, and a Venturi fertilizer injector was used to apply urea (0.33 kg $plant^{-1}$) through SRI–Supplied irrigation water. In stage III (June 20, 2016, and June 16, 2017), 0.3 kg $plant^{-1}$ of K_2O and 0.17 kg $plant^{-1}$ of urea were applied as topdressing (Li et al., 2015; Song et al., 2016). Each apple tree had one emitter located 30 cm from the trunk, buried at a depth of 40 cm, and positioned 30-cm east of the tree trunk (Fig. 3). Through each emitter, a 5.0 L h^{-1} flow rate was maintained.

2.3. Monitored and calculated data

2.3.1. Meteorological factors

Air temperature, relative air humidity, atmospheric pressure, solar radiation intensity, wind velocity, wind direction, and rainfall were recorded by an automated weather station every minute, record 1 time for every 30 min.

2.3.2. SWC

Using a TRIME-T3 tubular TDR (IMKO Ltd, DE), the vertical SWC profile was measured at 10-cm intervals over the 80-cm-deep soil layer at horizontal distances of 10, 20, and 30 cm from the emitter (Fig. 3). The irrigation quantity and date for the different treatments were recorded over the entire growth of the apple trees.

2.3.3. Fruit yield

The yield of apples from each treatment was weighed immediately after harvesting. The harvest dates were October 28 and 29 in 2016 and October 24 and 25 in 2017.

2.3.4. Fruit quality

After the fruit maturation stage, one fruit was taken from each of the upper, middle, and lower parts of an apple tree's eastern, southern, western, and northern aspects, resulting in a total of 12 fruits obtained per tree. The mean weight of these 12 fruits was calculated using the

Table 1
Profile of the uppermost 80 cm of soil at the beginning of the experiment.

Soil depth (cm)	Particle composition (%)			Bulk density ($g\ cm^{-3}$)	Field capacity (mass basis, %)	pH
	< 0.002 mm	0.02˜0.002 mm	2˜0.02 mm			
0˜20	1.66	21.76	76.58	1.26	22.8	8.5
≥20˜40	0.45	20.46	79.09	1.49	21.9	
≥40˜60	0.35	19.36	80.29	1.48	21.6	
≥60˜80	0.37	19.08	80.55	1.43	20.5	
Mean value	0.71	20.17	79.13	1.42	21.7	

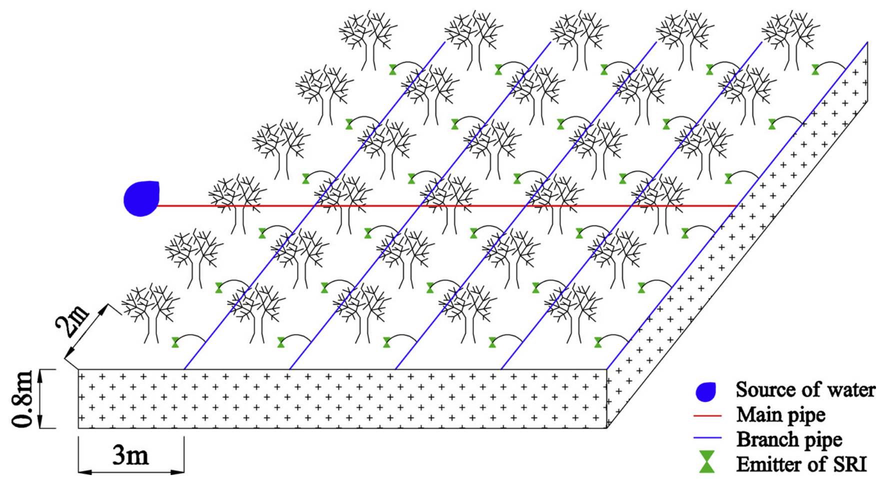

Fig. 2. Layout of the test irrigation system.

weighting method. Fruit firmness was measured using an FT-327-type fruit sclerometer in three positions—the upper, middle, and lower parts of the fruit—with the firmness in these three parts averaged to determine the actual fruit firmness. The vertical and horizontal diameters of each fruit were measured using a vernier caliper, and these diameters were used as the apple grade index; based on local classification, apples was divided into third grade ($r < 60$ mm), second grade ($60 \le r < 75$ mm), first grade ($75 \le r < 90$ mm), and special grade ($r > 90$ mm). First and special grade fruit were defined as excellent fruit, and the excellent-fruit percentage was calculated as number of excellent fruits/total number of fruits × 100%. A fruit's degree of coloration was measured using Photoshop and fruit photographic analysis, with all fruits photographed under the same lighting conditions. After selecting an area in a photograph, the redness (R) and brightness (L) were determined using the photograph's histogram, and R/L indicated the degree of coloration of the fruit. The fruits' water content was measured using the oven-drying method. Fresh fruits were first dried at 105 ℃ for 30 min and then dried at 70 ℃ until their weight did not change. Organic acid content was measured using the NaOH titration method, vitamin C (V_C) content was measured using the 2,6-dichloroindophenol sodium salt method, soluble solid content was measured using a WYT-1-type hold refraction instrument, and soluble reducing sugar content was measured using the thermal titration method with Fehling's reagent.

2.3.5. Evapotranspiration and WUE

The evapotranspiration (ET_C; mm) for the different treatments was obtained from the water balance formula (in the 80-cm-deep soil layer):

$$ET_C = \Delta W + I + P + G - D - R \tag{1}$$

where ΔW is the reduction of soil water storage between the beginning and end of the experiment (mm), and I, P, G, D, and R are the irrigation, effective rainfall, recharge of underground water, deep percolation, and runoff (mm), respectively.

The underground water at the experimental location was at more than 50 m below the ground level, and no runoff was generated during the growing season; thus, G and R were neglected. Eq. (1) could thus be simplified to

$$ET_C = \Delta W + I + P - D \tag{2}$$

The WUE (kg m^{-3}) was calculated as (Dai et al., 2019)

$$WUE = Y/ET_C \tag{3}$$

where Y is the yield (kg hm^{-2}) and ET_C is the evapotranspiration (m^3 hm^{-2}).

2.4. Data analysis

The data were analyzed using analysis of variance, performed with the SPSS statistical software (v. 21.0, SPSS Inc., 2013). Data for each year were analyzed separately. The significance of the treatment effect was determined using the F-test, and means were compared using the least significant difference (LSD) at the 5% level of significance.

3. Results

3.1. Water consumption of apple trees under RDI

As illustrated in Fig. 4, the water consumption of an apple tree over the entire growing season was 4590.74–7765.38 m^3 hm^{-2} in 2016 and 4770.36–7627.61 m^3 hm^{-2} in 2017. Compared with the NI treatment, RDI resulted in significantly higher water consumption ($P < 0.05$), but it exerted a significantly stronger water saving effect compared with the FI treatment. In 2016 and 2017, the percentage of water saved using RDI was in the ranges of 3.81%–32.77% and 2.63%–22.80% respectively. The order (from large to small) of water consumption of the apple trees in each stage was stage III, II, I, and IV. Water consumption during stage III was 59% and 71% of all water consumed over the entire growing season in 2016 and 2017, respectively, and this percentage was much higher than those for the other three growth stages. Water consumption during stage II was 11% and 21% of all water consumed over the entire growing season. In early October, the apple trees had entered stage IV; they consumed less water in stage IV than in other stages; water consumption in this stage ranged from 5% to 11%.

Comparing the water consumption of the apple trees subjected to the different water deficit treatments, water consumption decreased with an increase in the water deficit in the different growth stages, indicating that a water deficit actively inhibits transpiration. Compared with the FI treatment, the L and M treatments in the different growth stages decreased water consumption by 3.81%–9.11% and 6.30%–14.58% in 2016 and by 2.59%–8.95% and 5.18%–14.34% in 2017, respectively. When there was a water deficit at a certain growth stage, the treatment with a large water deficit resulted in higher water consumption after rehydration in the next stage. For example, compared with the L deficit treatment, when the M water deficit treatment was applied in stage III, water consumption in stage IV was 72.31% higher in 2016 and 18.77% higher in 2017.

3.2. Effect of RDI on apple quality

3.2.1. Physical fruit attributes

As detailed in Table 4, all water deficit treatments in the different

Table 2
Effective rainfall (mm) for each stage (month-day) of the 2016 and 2017 apple growing seasons.

Growing stage	Bud-burst to leafing stage (I)		Flowering to fruit set stage (II)		Fruit growth stage (III)		Fruit maturation stage (IV)		Whole growing season (W)	
	2016 4.19-5.21	2017 4.15-5.17	2016 5.22-6.19	2017 5.18-6.15	2016 6.20-10.5	2017 6.16-10.1	2016 10.6-10.28	2017 10.2-10.24	2016 4.19-10.28	2017 4.15-10.24
Effective rainfall	29.2	23.8	88.8	55.5	280.9	331.4	42.8	64.3	441.7	475.0

Table 3
RDI scheme.

Treatment	Soil water content (%θ_f)		
	Bud-burst to leafing stage (I)	Flowering to fruit set stage (II)	Fruit growth stage (III)
Full irrigation (FI)	85–100	85–100	85–100
I-L	70–85	85–100	85–100
I-M	55–70	85–100	85–100
I-S	40–55	85–100	85–100
II-L	85–100	70–85	85–100
II-M	85–100	55–70	85–100
III-L	85–100	85–100	70–85
III-M	85–100	85–100	55–70
No irrigation (NI)	/		

growth stages resulted in higher fruit firmness, although significant differences were observed among the treatments. In 2016 and 2017, the highest fruit firmness of 7.6 and 7.4 kg cm^{-2}, respectively, was obtained with the III–M treatment, and for the FI treatment, the highest firmness was 6.3 and 6.1 kg cm^{-2}. Fruit firmness was higher for greater water deficits. In both years, a water deficit during stage III improved fruit firmness significantly ($P < 0.05$) when compared with the FI treatment.

The different water deficit treatments in the different growth stages had no significant effect on the degree of coloration ($P > 0.05$). However, water deficit treatment had a significant effect on single fruit weight ($P < 0.05$). In both years, the I–L and II–L treatments significantly increased the single fruit weight ($P < 0.05$). Compared with the FI treatment, the single fruit weight after the I–L and II–L treatments was 4.17% and 9.69% higher in 2016 and 3.16% and 4.40% higher in 2017, respectively. The I–M, I–S, and II–M treatment had no significant effect on single fruit weight ($P < 0.05$). Water deficit treatment in stage III resulted in lower single fruit weight, and single fruit weight was significantly lower in the M treatment ($P < 0.05$).

As indicated in Table 4, the different water deficit treatments in the different growth stages affected the percentage of apples considered excellent quality. Compared with the FI treatment, the III–L and III–M treatments resulted in a significantly lower excellent-fruit percentage ($P < 0.05$): 15.24%–20.36% lower in 2016 and 15.27%–18.45% lower in 2017. The excellent-fruit percentage was improved with the I–L, I–M, II-L, and II–M treatments and increased significantly with the I–L treatment in 2017 and the II–M treatment in 2016 ($P < 0.05$).

3.2.2. Chemical fruit attributes

Water deficit treatment in the various growth stages improved the fruit quality (Table 5). The 2-year results demonstrated that a greater water deficit resulted in lower water content. Water deficit treatment during stages II and III significantly decreased water content ($P < 0.05$), but the effect was nonsignificant for treatment in stage I ($P > 0.05$). Water deficit treatment had the greatest effect on water content when used in stage III. Compared with the FI treatment, the III–L and III–M treatments resulted in 4.26% and 5.26% lower water content in 2016 and 5.58% and 10.07% lower water content in 2017, respectively.

Compared with water content, water deficit treatment had the opposite effect on soluble solid and reducing sugar content; both were increased when the water deficit was greater. In both years, water deficit treatment in stage I had no significant effect on soluble solid content ($P > 0.05$), but treatment in stages II and III significantly increased soluble solid content ($P < 0.05$). Soluble reducing sugar content was significantly affected by water deficit treatment ($P < 0.05$) during the different growth stages in 2016 and 2017. Compared with the FI treatment, water deficit treatment in stage II resulted in soluble reducing sugar content that was 15.85%–28.34% higher in 2016 and 15.42%–31.45% higher in 2017. In both years, the largest soluble

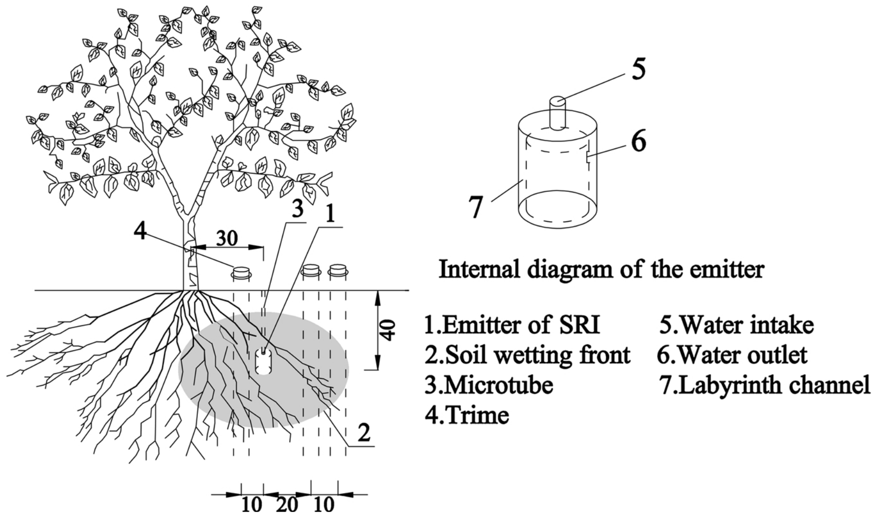

Fig. 3. Emitter and TDR arrangement of SRI.

reducing sugar content, 17.98% in 2016 and 17.64% in 2017, was obtained with the II–M treatment.

The effects of water deficit treatment on the organic acid and V_C content of the fruit were nonsignificant ($P > 0.05$). The organic acid content of the apples was mainly affected by respiration and the application of potassium fertilizer rather than by the water deficit.

The presented results indicated that using the different water deficit treatments during the different growth stages affected the quality indices of the apples. Water deficit treatment mainly enhanced fruit firmness, single fruit weight, excellent-fruit percentage, and soluble solid and soluble reducing sugar content but reduced water content, indicating that water deficit treatment can regulate the quality of apples. Water deficit treatment during stage II caused a slight increase in fruit firmness and a slight decrease in fruit water content, which made these apples ideal for storage; additionally, the single fruit weight, excellent-fruit percentage, and soluble solid and soluble reducing sugar content were significantly improved, making the apples sweeter. Therefore, water deficit treatment during stage II had a significant positive effect on apple quality, with the II–M treatment being optimal and the II–L treatment being second best.

3.3. Effect of RDI on apple yield and WUE

As illustrated in Fig. 5, the relationship between the apple yield and water consumption was not linear, and the FI treatment, which consumed the most water, did not result in the highest yield. In both years, the I–L, I–M, II–L, and II–M treatments resulted in higher yield than the FI treatment, with this effect was found to be significant for the II–L and II–M treatments ($P < 0.05$). The highest yield of 42,416.9 and 43,866.7 kg hm^{-2} in 2016 and 2017, respectively, was obtained with the II–L treatment. The yield under RDI treatment was significantly higher than that under the NI treatment ($P < 0.05$), indicating that RDI can effectively increase the yield.

By comparing with the yield obtained using the FI treatment, water deficit treatment during stage I had no significant effect on yield ($P > 0.05$) in either year. Compared with the FI treatment, the II–L and II–M treatments resulted in 13.93% and 13.28% higher yield in 2016 and 17.94% and 17.13% higher yield in 2017, respectively, indicating that water deficit treatment during stage II actively increases the fruit yield. This was because a water deficit during stage II inhibits the growth of new shoots and leaves, which is conducive to fruit formation. However, water deficit treatment during stage III significantly reduced the fruit yield ($P < 0.05$) in both years. Compared with that obtained using the FI treatment, the fruit yield obtained using the III–L and III–M treatments was 10.89% and 13.46% lower in 2016 and 3.66% and 10.10% lower in 2017, respectively. This was because the water consumed during stage III is mainly for fruit growth; a water deficit thus directly affects the yield.

Fig. 5 also shows that water deficit treatment increased the WUE by 1.31%–26.16% in 2016 (except for III–L) and 4.85%–19.49% in 2017. The WUE of the apple trees was larger in the II–L and II–M treatments (greater than 7 kg m^{-3}). The WUE was smaller with the FI treatment, which consumed the most water, and the NI treatment, which consumed the least water (6.13 and 5.03 kg m^{-3} in 2016 and 5.97 and

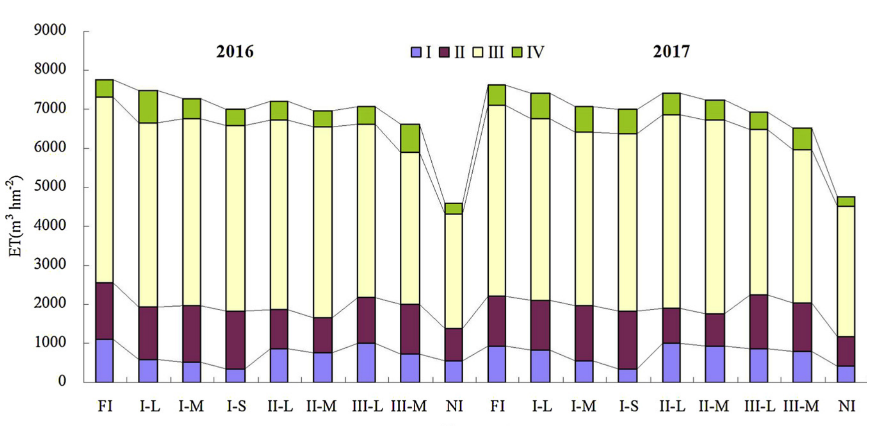

Fig. 4. Evapotranspiration in different growth stages under different water deficit levels in 2016 and 2017.

Table 4
Effect of water deficit during different growth stages on physical attributes.

Treatment	2016				2017			
	Coloring degree	Single fruit weight (g)	Fruit firmness ($kg\ cm^{-2}$)	Excellent fruit percentage (%)	Coloring degree	Single fruit weight (g)	Fruit firmness ($kg\ cm^{-2}$)	Excellent fruit percentage (%)
FI	1.95 ± 0.41a	221.75 ± 26.48b	6.3 ± 0.8c	57.95 ± 6.84b	2.15 ± 0.32a	234.75 ± 34.11b	6.1 ± 0.8c	55.87 ± 5.32b
I-L	1.65 ± 0.12b	231.96 ± 23.59a	6.4 ± 0.6c	59.12 ± 3.49ab	2.10 ± 0.26a	242.17 ± 24.74a	6.2 ± 0.7c	62.86 ± 4.41a
I-M	1.85 ± 0.22ab	225.45 ± 42.56ab	6.8 ± 1.0bc	58.16 ± 4.31b	1.91 ± 0.25b	223.19 ± 41.09bc	6.2 ± 0.8c	60.22 ± 5.79ab
I-S	1.81 ± 0.37ab	217.37 ± 30.17b	6.9 ± 0.9bc	51.12 ± 8.56bc	2.08 ± 0.22a	227.37 ± 37.42bc	6.5 ± 1.1bc	53.12 ± 7.50bc
II-L	1.87 ± 0.63ab	243.23 ± 33.45a	6.4 ± 0.8c	60.32 ± 3.67ab	1.90 ± 0.13b	245.08 ± 25.90a	6.3 ± 0.6c	64.11 ± 2.11a
II-M	1.95 ± 0.21a	234.45 ± 28.79ab	6.5 ± 0.9bc	63.12 ± 4.33a	2.19 ± 0.16a	237.95 ± 32.08ab	6.2 ± 0.4c	61.12 ± 5.94ab
III-L	2.06 ± 0.52a	215.56 ± 21.15bc	7.1 ± 0.3b	49.12 ± 4.18c	2.11 ± 0.31a	221.79 ± 33.42bc	6.9 ± 0.5ab	47.34 ± 3.97c
III-M	2.05 ± 0.23a	205.15 ± 12.98c	7.6 ± 1.0ab	46.15 ± 8.90cd	2.15 ± 0.14a	208.19 ± 22.04d	7.4 ± 1.5a	45.56 ± 7.16cd
NI	1.96 ± 0.44a	184.96 ± 33.45d	8.1 ± 0.4a	40.15 ± 6.86e	2.16 ± 0.21a	193.31 ± 30.28e	7.9 ± 0.7a	42.01 ± 5.23e

For each year, values within a column followed by a different letter are significantly different at $P < 0.05$ according to an least significant difference (LSD) test.

$5.19\ kg\ m^{-3}$ in 2017, respectively); both WUE values were lower than $6.2\ kg\ m^{-3}$. The WUE of then trees treated with a water deficit during stage III was low, whereas that of the trees treated with a water deficit during stage II was high. The highest WUE was obtained for the II–M treatment ($7.74\ kg\ m^{-3}$ in 2016 and $7.38\ kg\ m^{-3}$ in 2017).

By comparing the fruit yield and WUE of the apple trees, the fruit yield and WUE were lower when a water deficit was applied during stage III; therefore, water deficit treatment should not be applied during stage III, and sufficient irrigation should be maintained during this stage. When the I–L and I–M water deficit treatments were employed, the fruit yield and WUE of the trees were higher than those obtained when the FI treatment was used; thus, L and M water deficit treatments should be applied in stage I. However, the optimal stage for water deficit treatment is stage II, during which the fruit yield and WUE of the trees were the maximum.

4. Discussion

4.1. Water consumption of apple trees under RDI

Xu (2016) studied the water demand regulation of the Apple Park on the Loess Plateau in China and discovered that supplementary irrigation is required during stages I and II and the early part of stage III of a normal hydrological year, and that the rainfall during late stage III and during stage IV meets the water demand of apple trees without the need for irrigation. Rainfall in 2016 and 2017 was plentiful; therefore, the S water deficit treatment ($40\%\theta_f$ –$55\%\theta_f$) was not employed in stages II and III, and water deficit treatment was not applied in stage IV.

Numerous studies have shown that the main water consumption period of apple trees is from June to October; water consumption increases slowly in stage I, increases rapidly in stage II, peaks in stage III, and is low in stage IV (Chenafi et al., 2016; Song et al., 2018). Su et al. (2005) discovered that when drip irrigation was employed, the water consumption profile of apple trees over the whole growth period exhibited a single peak. Water consumption gradually began to increase in early April, peaked in July, and decreased after August. Guo (2006) used Fuji apples grown in dry lands as the research object and obtained results regarding water consumption regulation in a drought year that were consistent with the results of Su et al. (2005), with water consumption intensity peaking from the end of June to the beginning of July. The present study discovered that the water consumption of the apple trees during the four growth stages were in the order stage III > II > I > IV, which was similar to previous research findings. Generally, the temperature during stage I of apple tree growth is lower than that during other stages, and the light intensity is weaker. Stage I is mainly for the germination and initial growth of leaves to accumulate sufficient water (Kucukyumuk et al., 2013); therefore, transpiration and evaporation are weaker, and water consumption is lower. With the increasing temperature, apple trees enter stage II in late May, and during this period, new shoots emerge on the apple trees, flower buds differentiate, and the leaves enter their initial period of rapid growth (Zhou et al., 2015); water consumption thus increases, accounting for approximately 10%–20% of the total water consumption over the entire growth period. In mid-June, apple trees enter stage III of growth, which is the period determining the final yield and fruit quality (Zheng et al., 2017). In the present study, the water consumed during stage III was 59% and 71% of all water consumed over the entire growing season in 2016 and 2017, respectively, which is much higher than the percentages for the other growth stages. This was due to the high temperature and strong solar radiation during this period, which promoted fruit development and rapid leaf growth; transpiration and evaporation were thus stronger, and water consumption was higher. Stage IV of apple tree growth occurred in early October. During this period, the temperature was lower—approximately 8 ℃ on average—and the sunshine hours were decreased; relative humidity was higher due to increased rainfall (Dai et al., 2019). Additionally, the vegetative organs of the apple trees stopped growing, and the leaves began to wither and fall off under the influence of temperature. Fruit growth was not significant during this period, and the growth of the apple trees was relatively stable (Zhou et al., 2015); thus, water consumption was low, accounting for 5% and 11% of all water consumed over the growing season.

Studies have demonstrated that water consumption decreases with an increase in the water deficit during the different growth stages (Cheng et al., 2012; Cui et al., 2008; Qiang et al., 2015), indicating that water deficit treatment actively inhibits transpiration, which was confirmed in this study. This may be because a water deficit changes the distribution of photosynthate between the roots and crowns of fruit trees (Cui et al., 2009); that is, the roots obtain more assimilation products, which is conducive to later growth and development. When the growth of crowns is inhibited, leaf area is reduced, thereby reducing transpiration.

4.2. Effect of RDI on apple quality

This study demonstrated that RDI can increase fruit firmness, which is similar to the conclusions of Marsal et al. (2010); Cuevas et al. (2007); Bussakorn et al. (2002), and others. This is because a water deficit limits the expansion and division of pulp cells, resulting in the higher density of pulp cells. In this study, fruit firmness increased with an increase in the water deficit; this may be because insufficient SWC inhibits the activity of biological enzymes and degradation of cell wall cellulose and pectin. Water deficit treatment during stages I, II, and III had no significant effect on degree of fruit coloration in either year ($P > 0.05$). This may have been because the optimal environment for the development of the color of apples should be provided in stage IV, during which sufficient illumination time of 6–8 h should be maintained, and the average daily temperature should be 12.8 °C (Zeng, 2017). In the present study, the climate in stage IV in 2016 was only slightly different to that in 2017, so the apples grown in these two years had only small differences in coloration.

Table 5
Effect of water deficit treatment during different growth stages on the chemical attributes of apples.

Treatment	2016					2017				
	Water content (%)	Soluble solid (%)	Soluble reducing sugar (%)	Organic acid (%)	Vitamin C(V_C) (μg $100g^{-1}$)	Water content (%)	Soluble solid (%)	Soluble reducing sugar (%)	Organic acid (%)	Vitamin C(V_C) (μg $100g^{-1}$)
FI	86.71 ± 4.15a	10.41 ± 0.24d	14.01 ± 1.26c	0.34 ± 0.11b	0.59 ± 0.21a	89.12 ± 5.61a	10.15 ± 2.12d	13.42 ± 2.45c	0.36 ± 0.06a	0.55 ± 0.15a
I-L	85.72 ± 3.02a	10.52 ± 0.80d	15.47 ± 1.62bc	0.35 ± 0.08b	0.56 ± 0.16a	88.77 ± 2.71a	10.99 ± 1.13d	13.79 ± 2.71c	0.32 ± 0.17ab	0.54 ± 0.11a
I-M	85.32 ± 3.42a	10.62 ± 0.71d	16.25 ± 1.24b	0.34 ± 0.09b	0.58 ± 0.11a	88..53 ± 3.51a	10.26 ± 0.82d	14.25 ± 1.02b	0.33 ± 0.14ab	0.50 ± 0.04ab
I-S	85.05 ± 3.99ab	11.23 ± 1.24cd	16.64 ± 2.07b	0.35 ± 0.15b	0.53 ± 0.14ab	87.16 ± 4.65ab	11.52 ± 0.97c	16.98 ± 2.11a	0.32 ± 0.08ab	0.48 ± 0.21b
II-L	85.33 ± 5.41ab	11.95 ± 1.23c	16.23 ± 2.11b	0.33 ± 0.15bc	0.59 ± 0.05a	86.45 ± 6.64b	11.46 ± 0.82c	15.49 ± 3.12ab	0.37 ± 0.11a	0.56 ± 0.09a
II-M	84.21 ± 3.54b	12.02 ± 1.06c	17.98 ± 2.56a	0.34 ± 0.16b	0.62 ± 0.09a	85.15 ± 5.34bc	12.52 ± 0.97bc	17.64 ± 2.15a	0.38 ± 0.12a	0.54 ± 0.14a
III-L	83.02 ± 4.22bc	11.85 ± 0.78c	15.65 ± 1.35bc	0.37 ± 0.16a	0.61 ± 0.18a	84.15 ± 3.56c	12.36 ± 0.56bc	14.78 ± 1.22b	0.35 ± 0.06a	0.54 ± 0.23a
III-M	82.15 ± 3.27c	12.66 ± 1.26bc	17.02 ± 2.36ab	0.36 ± 0.17ab	0.51 ± 0.20ab	80.15 ± 4.56d	13.56 ± 0.87b	15.62 ± 1.09ab	0.32 ± 0.09ab	0.53 ± 0.19a
NI	78.82 ± 4.68e	13.99 ± 0.24a	17.06 ± 1.23ab	0.32 ± 0.12c	0.49 ± 0.11b	80.56 ± 4.47d	14.85 ± 1.35a	17.01 ± 2.23a	0.31 ± 0.03b	0.43 ± 0.18b

For each year, values within a column followed by a different letter are significantly different at $P < 0.05$ according to an least significant difference (LSD) test.

RDI can reduce the final single fruit weight and volume (Cuevas et al., 2007; Leib et al., 2006), In the present study, the I–M and I–S treatments had little effect on the single fruit weight and volume, whereas the III–L and III–M treatments significantly reduced them, indicating that water deficit treatment in stage I had a weaker effect on weight and volume than did stage III. A possible reason is that a water deficit during stage I significantly inhibited the vegetative growth of the fruit trees (Cui et al., 2009), so that some of the photosynthate accumulated in the plants, providing crucial energy for the reproductive growth of the trees when entering stage II. Additionally, the compensation effect after the water deficit would greatly increase the photosynthetic rate and be more conducive to energy storage (Kou et al., 2014). Thus, treatment in stage I did not reduce the single fruit weight and volume. Stage III is a critical period for the development of flesh cells, and a water deficit seriously inhibits the expansion of flesh cells, which may cause the single fruit weight and volume to decrease significantly. In this study, water deficit treatment during stage II resulted in the increased single fruit weight and volume. This may have been because a water deficit during stage II leads to the wilting of flower buds, affecting the completion of the pollination process (Rodríguez et al., 2007) and causing young fruit to fall off. The surviving fruit would have more nutrients and a greater water supply, thus increasing the single fruit weight and volume. Ansari et al. (2018) demonstrated that the application and subsequent relief of water stress promote fruit growth, thus resulting in larger fruit.

Water deficit treatment increased soluble solid and soluble reducing sugar content in a previous study (Leib et al., 2006), which is in agreement with our result. Verreynne et al. (2001) indicated that water deficit treatment increased the organic acid content of citrus by 11%–13%. However, the present study found that water deficit treatment had no significant effect on apples' organic acid content, which is consistent with the findings of Bussakorn et al. (2002), indicating that the effect of a water deficit on the organic acid content of fruit varies greatly according to the fruit variety. Water deficit treatment during the different growth stages has been found to increase the sugar/acid ratio (Alikhani-Koupaei et al., 2018; Grinan et al., 2019), in agreement with our result. The difference in the increased sugar/acid ratio between 2016 and 2017 may have resulted from the temperature difference and water stress during III stage in both years. Chen et al. (2005) also indicated that high temperature and drought result in an increased sugar/acid ratio.

4.3. *Effect of RDI on apple yield and WUE*

Numerous field experiments have shown that crops have certain adaptability to water deficits. Timely and moderate water deficits partially inhibit the growth of vegetative organs but do not significantly reduce crop yield (Cui et al., 2009; Qiang et al., 2015). This may be because the growth of crop reproductive organs and vegetative organs is mutually dependent and competitive. When crops are subjected to water stress, they have the ability to minimize damage, prevent species extinction, and redistribute nutrients through self-regulation (Wang et al., 2015; Yang et al., 2015). This is the theoretical basis for the water saving effects of RDI and its ability to maintain or even increase yield. In this study, water deficit treatment during stage I had no significant effect on the apple yield ($P > 0.05$), whereas such treatment during stage III significantly reduced the yield ($P < 0.05$). Leib et al. (2006) also discovered that moderate water deficit treatment during stage III significantly decreased the apple yield. The possible reason is that stage I is the initial stage of vegetative organ growth in apple trees, during which water accumulates for use in flower bud differentiation; a moderate water deficit in stage I may not cause much reduction in crop yield (Kang and Cai, 2002). In a previous study, the growth rate of vegetative organs in the stage III of apple tree growth was slow, and water was mainly consumed for the growth and development of reproductive organs (Cui et al., 2008). A water deficit during stage III can

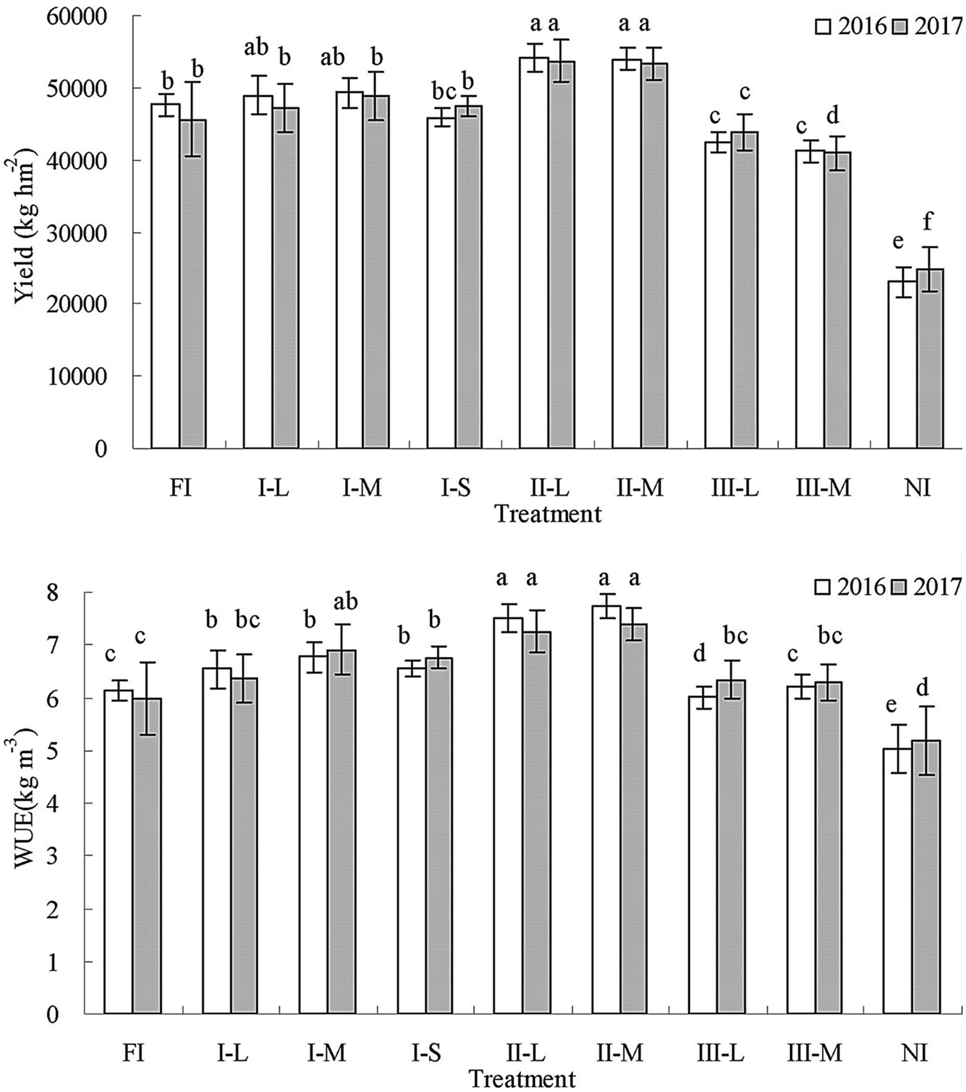

Fig. 5. Fruit yield and WUE under different water deficit levels in different growth stages in 2016 and 2017. Different letters indicate values that are significantly different at the $P < 0.05$ level for comparisons within same year. Error bars represent standard deviations.

restrict photosynthesis, which reduces the assimilates produced through photosynthesis; conversely, fruit tissue expansion is sensitive to water deficits. Therefore, a water deficit inevitably influences the growth of fruit tissue and results in a decreased fruit yield. The present study demonstrated that the L and M water deficit treatments during stage II significantly increased the fruit yield ($P < 0.05$). Qiang et al. (2015) also reported that the moderate water deficit treatment during stage II promoted the growth and yield of jujube fruits and improved the WUE. This is perhaps because the growth of shoots and leaves is inhibited when a water deficit is applied during stage II, which is conducive to fruit formation. Gucci et al. (2019) also indicated that suitable water stress during stage II could inhibit the growth of vegetative organs; rather than accumulating in vegetative organs, organic matter accumulated in reproductive organs, promoting fruit growth.

5. Conclusions

Experiments applying RDI of varying degrees during the different apple tree growth stages indicated that RDI saved significantly more water than FI. Our results revealed that water deficit treatment had significant effects on the fruit quality, fruit yield, and WUE of the apple trees. The optimal period for water deficit treatment was discovered to be the flowering to fruit set stage, during which the yield and WUE of apple trees were the highest. In addition, water deficit treatment during the flowering to fruit set stage had a significantly positive effect on apple quality; controlling SWC to be $55\%\theta_f$ –$70\%\theta_f$ obtained the best results, and controlling SWC to be $70\%\theta_f$ –$85\%\theta_f$ obtained the second best results. Therefore, the optimal water deficit treatment involves controlling SWC to be $55\%\theta_f$ –$70\%\theta_f$ during the flowering to fruit set stage. Such treatment can enhance the fruit quality, fruit yield, and WUE of apple trees in water-scarce environments. However, because considerable rainfall occurred in 2016 and 2017, the S water deficit treatment could not be applied due to excessive rainfall during the flowering to fruit setting and fruit growth stages, and further study is required to the effects of the S water deficit treatment. In addition, research investigating the effect of water deficits during compound stages and multiple stages should be conducted in the future.

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