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Subsurface irrigation with ceramic emitters: An effective method to improve apple yield and irrigation water use efficiency in the semiarid Loess Plateau

Yaohui Cai [a,b,c], Pute Wu [a,b,c,*], Delan Zhu [c], Lin Zhang [a,b,c], Xining Zhao [a,b,c], Xiaodong Gao [a,b,c], Maosheng Ge [c], Xiaolin Song [c,e], Yong Wu [d], Zhiguang Dai [f]

[a] Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China
[c] Institute of Water-Saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling 712100, China
[d] National Agricultural Technology Extension Service Center, Chaoyang, Beijing 100026, China
[e] The College of Horticulture, Northwest A&F University, Yangling, Shaanxi 712100, China
[f] College of Agricultural Engineering, Henan University of Science and Technology, Luoyang, Henan 471003, China

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ABSTRACT

Apple trees consume a large amount of water, causing soil desiccation which reduces the land quality in the Loess Plateau. The development of efficient water-saving irrigation technology has become the main way to maintain apple production and prevent land degradation in this area. Subsurface irrigation with ceramic emitters (SICE) is an energy-efficient and water-saving technology for arid and semi-arid regions. However, the effectiveness of SICE for apple trees needs to be researched because of the special environment of the Loess Plateau. In this study, we determined the optimal buried depth of SICE tape, based on the soil water content (*SWC*), yield, water use efficiency (*WUE*) and irrigation water use efficiency (*IWUE*) of apple trees over a two-year field experiment. Results shown that SICE buried at a depth of 40 cm significantly improved new shoot length, yield, *WUE* and *IWUE* by 15.9%, 7.6%, 14.8% and 6.5% respectively compared to subsurface drip irrigation (SDI). Variations in *SWC* for SICE buried at a depth of 40 cm were smaller than those for SDI. SICE significantly enhanced yield through its ability to save water and increase soil temperature for apple trees. Our study shows that SICE did not only produce a suitable soil water environment and ensure stable growth of apple trees, but also saved more water resources.

1. Introduction

The Loess Plateau is the main apple growing area in the world, with approximately 27% of the current global harvest supplied from this region (Wang et al., 2020). Large-scale planting of apple trees can damage the native vegetation ecosystems, resulting in serious soil loss (Kalhoro et al., 2018; Jia et al., 2019). Land degradation can occur because apple trees consume large volumes of soil water, leading to the formation of dry soil layers (Li et al., 2019; Jia et al., 2020). Moreover, reduced and unevenly distributed precipitation has not been properly utilized, causing extensive soil erosion in the rainy season, and affecting the growth of apple trees due to lack of water in the dry season (Gao et al., 2018a; Gao et al., 2018b). Two strategies were adopted to increase apple production in the area. The first enhanced the ability of apple trees to adapt to climate change, and the second promoted the use of high-efficiency water-saving irrigation measures (Shao et al., 2019). Both strategies increased productivity by making full use of precipitation resources without over-exploiting scarce groundwater resources (Akhtar et al., 2016; Qiu et al., 2018).

Over recent years, numerous water-saving methods have been used in northwest China, including alternate partial root-zone irrigation and surge-root irrigation (Dai et al., 2019; Qi et al., 2020). Burnham et al. (2015) surveyed 13 villages in the Loess Plateau and identified two with experience of using drip irrigation for corn and vegetable crops. The drip irrigation system was shown to operate efficiently and met farmers' expectations. However, the use of drip irrigation is limited by expensive

* Correspondence to: No. 22, Xinong Road, Yangling 712100, Shaanxi, China.
E-mail addresses: gjzwpt@vip.sina.com (Y. Cai), gjzwpt@vip.sina.com (P. Wu).

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initial investment costs and a complex management system. Wang et al. (2014) installed a drip irrigation system for growing maize in the Loess Plateau and observed a peak in irrigation water use efficiency (*IWUE*) with an acceptable yield for a dripper discharge of 3 L/h, a 6-day irrigation frequency and 80% evaporation. Zhong et al. (2019) found that the water deficit present during the flowering to fruit set stage had a significant positive effect on the quality, yield, and *WUE* of apple trees when surge-root irrigation was used in the Loess Plateau. Essentially, the use of water-saving irrigation improves agricultural production and farmers' incomes, and results in the efficient use of water resources (Liu et al., 2019). However, high initial and operational costs are likely to be the key constraints preventing further applications. In such irrigation systems, a large amount of electricity is used by pumps, and the initial cost of the pump is expensive. In order to reduce costs, irrigation systems that require a lower working pressure and can function without pumps are preferred. Moreover, Ayars et al. (2017) found that soil water content (*SWC*) was maintained within a narrow range by using high-frequency drip irrigation during the irrigation season. Fan et al. (2019) determined that a slight alteration to *SWC* when using high-frequency irrigation could produce a high yield and increase the quality of organic melons. Therefore, irrigation methods that maintain *SWC* within a narrow range whilst also functioning under low pressures should be prioritized.

Cai et al. (2017) recently developed a subsurface irrigation method using ceramic emitters (SICE). The working pressure heads of this system are generally smaller than 100 cm (Paredes and San Jose, 2019). Cai et al. (2018) found that the ceramic emitter discharge decreased over time for negative or zero working pressures. A value of 0 L/h was observed when the soil moisture reached saturation and the ceramic emitter was consequently able to resume efficient operation when the soil moisture became depleted. Feedback regulation was observed between the *SWC* and emitter discharge (Kacimov and Obnosov, 2016). The *SWC* can be kept relatively stable over time, which may be beneficial for crop growth. A substantial amount of research has been carried out on SICE, including preparation technology and the seepage characteristics of ceramic emitters (Abu-Zreig et al., 2018; Chen et al., 2019). However, current research on the effect of SICE on plant growth is lacking. SICE may have great potential as an effective irrigation method in the Loess Plateau, providing a favorable water environment for apple trees while increasing apple yield and quality.

There are many factors that affect the irrigation quality of SICE, such as the buried depth and emitter discharge, with the buried depth significantly affecting the root distribution of apple trees. A suitable buried depth of subsurface drip irrigation (SDI) can significantly optimize the crop root distribution, enhance root activity, promote soil nutrient uptake, and increase yield and water use efficiency (Li and Liu, 2011; Elnesr et al., 2015). Selecting the appropriate drip tape depth for different crops is a crucial step in the irrigation management process. Bozkurt and Mansuroglu (2018) found that varying drip tape placement depths significantly affected green bean yields in the spring growing cycle, with the maximum yield observed for a buried depth of 10 cm. Moreover, Patel and Rajput (2007) recommended an SDI drip tape placement depth of 10 cm for peak potato yields, while Ghazouani et al. (2016) identified an optimal installation depth of approximately 15 cm to maximize eggplant *IWUE* in sandy soils. However, the optimal SDI drip tape placement depth for each crop is known to be a function of soil type. As SICE is a subsurface irrigation method, its operating system differs from that of SDI, and research comparing the two systems is limited.

Based on the limitations in the literature and the bottlenecks in current irrigation systems, the objectives of this study were as follows: (1) to evaluate the performance of SICE and (2) to determine the optimal buried depth of SICE tape based on the *SWC*, yield, *WUE* and *IWUE* of apple trees in the Loess Plateau.

2. Materials and methods

2.1. Study site and field conditions

The field experiment was carried out at a modern agricultural demonstration park (110°02′30″E，37°27′07″N; 957 m above sea level) in Zizhou County, Yulin, in the northern region of the Loess Plateau, northwest China (Fig. 1). The experiments were carried out from March 2017 to October 2018 over a field area of 50 × 21 m^2. The Loess Plateau is a dryland agriculture region, with a typical continental monsoon climate and an average annual temperature of 9.1 °C. In the summer months, the weather is extremely hot, while in winter, it is mild and slightly windy, with a frost-free period of approximately 145 days. Average perennial precipitation is approximately 428.1 mm, with 60–70% of precipitation occurring from July to September. The mean annual pan evaporation is 1087.7 mm (Li et al., 2017).

2.2. Soil properties

The soil type of the study site was almost loamy sand (USDA) down to 100 cm. Soil samples were taken at the beginning of the experiment at depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. The physical and chemical soil properties were measured using the method described by Yang et al. (2020), and are shown in Table 1.

2.3. Experimental design

Experiments were carried out in an orchard with apple trees (*Malus pumila Mill*) planted in 2012 with 2 m and 3 m spacing (Fig. 1). Standard agronomic measures, such as trimming, girdling, spraying insecticide and weed control, were the same for all treatments to maintain relatively healthy crops, and avoid unnecessary yield losses. The growing season of the apple trees was divided into four stages, as shown in Table 2. Five treatments were established as follows: S1H1 (SICE buried depth of 20 cm); S1H2 (SICE buried depth of 40 cm); S1H3 (SICE buried depth of 60 cm); S3H2 (SDI buried depth of 40 cm); and CK (control, no irrigation treatment). Each of the five treatments had three replicates in a row, with four trees included in each replicate, and a plot area of 24 m^2.

2.3.1. SICE system

A typical SICE system consists of 6 parts: water harvesting surface, water tank, submain pipe, lateral, ceramic emitters, and blow-off valves (Fig. 2a). Fig. 2b shows the SICE system that was installed in May 2017 in the apple orchard. Irrigation water was supplied to each plot through plastic pipes fed by a water tank in the apple tree field. Trees irrigated using the SICE system had a ceramic emitter for each plant installed 90 cm from one side of the tree (Fig. 2c). The ceramic emitter used in the experiment was a hollow cylinder with dimensions 70 mm × 40 mm × 20 mm (length × external diameter × inner diameter) and a hydraulic conductivity of 0.179 cm/h. The relationship between the emitter discharge in air (mL/h) and the working pressure head (cm) was . The supply of irrigation water to the apple trees through the SICE system was continuous from the bud burst stage through to fruit maturity, with a working pressure head of 20–50 cm. Since SICE is a continuous irrigation method, biological clogging can easily occur. To prevent this happening, two methods were used during the experiment. One method was to cover the water tank with a black plastic cloth, and the other was to set up an emptying valve at the end of the lateral so that the irrigation water could be completely emptied from the system after the apples were harvested. The irrigation pipe network was flushed before use in the second year.

2.3.2. SDI system

A typical SDI system consists of water source, pump, submain pipe, lateral, emitters, and valves. The SDI system was also installed in May 2017. Irrigation water was supplied from a reservoir located 70 m above

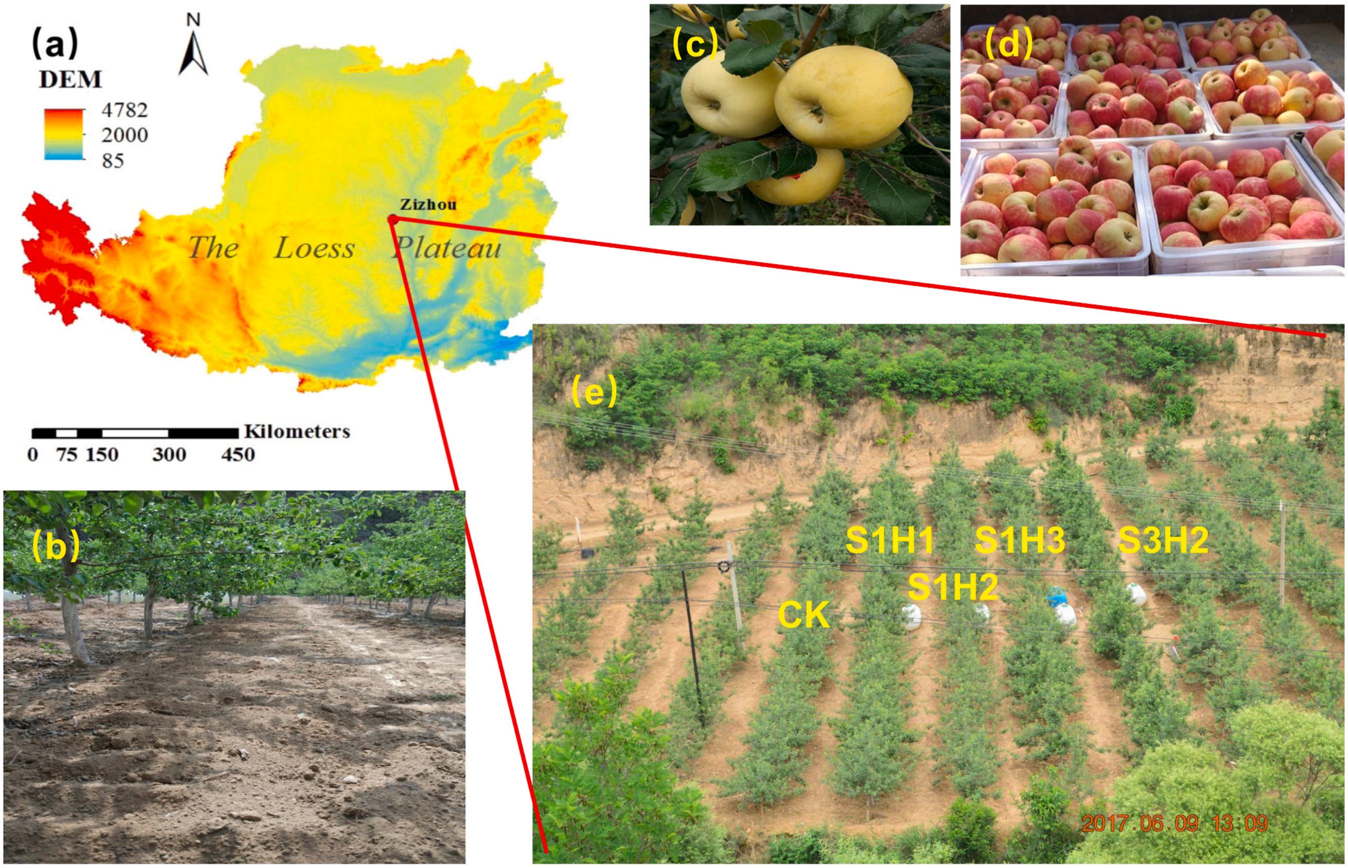

Fig. 1. Location of the study area in the northern region of the Loess Plateau (a); Irrigation pipelines buried in the soil (b); apple in the fruit expansion stage (c); apple after maturity (d); experiment treatments in the field (e).

Table 1
Chemical and physical properties of soils in the 0–100 cm mineral soil layer.

Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Texture Class	Soil bulk density (g cm^{-3})	pH	Field Capacity (cm^3 cm^{-3})	N Content (mg kg^{-1})	P Content (mg kg^{-1})	K Content (mg kg^{-1})	Organic Matter (%)
0–10	0.38	16.39	83.23	Loamy sand	1.28	8.30	0.28	22.3	9.9	257.4	0.79
10–20	0.53	17.96	81.51	Loamy sand	1.33	8.20	0.29	22.4	10.2	250.2	0.81
20–40	0.55	18.28	81.17	Loamy sand	1.40	8.50	0.30	22.9	11.9	268.7	0.81
40–60	0.58	16.28	83.15	Loamy sand	1.41	8.60	0.31	23.4	12.1	258.2	0.91
60–80	1.04	31.72	67.24	Sandy loam	1.46	8.50	0.29	24.1	11.4	281.1	0.82
80–100	0.75	24.30	74.95	Loamy Sand	1.41	8.70	0.29	20.3	10.9	258.3	0.79

Note: the average field capacity is 0.29 cm^3 cm^{-3}.

Table 2
Stages of the apple growing season in the Loess Plateau.

Year	Bud Burst to Leafing (Stage I)	Flowering to Fruit Set (Stage II)	Fruit Expansion (Stage III)	Fruit Maturity (Stage IV)
2017	4/05–5/24	5/25–6/30	7/01–9/01	9/02–9/15
2018	4/01–5/19	5/20–6/25	6/26–8/29	8/30–9/20

the apple tree field, and fed to each plot through plastic pipes using a pump. The SDI tape was installed 90 cm from one side of the tree, with an emitter spacing of 30 cm. The working pressure head of the emitter was 1000 cm and the emitter discharge was 1.10 L/h. A flow meter was used to measure the amount of water used in each treatment.

2.3.3. Irrigation schedule

The irrigation schedules for SICE and SDI were different, with continuous irrigation for the former and intermittent irrigation (alternate watering and drying) for the latter. Fig. 3 shows the amount of irrigation water used by the SICE and SDI treatments for 2017 and 2018. The irrigation of the apple trees in the Loess Plateau started on 18 May in 2017 and on 3 April in 2018.

The irrigation schedule for SDI was consistent with the irrigation measurements by local farmers that year. The irrigation amount was approximately 8 mm for each SDI irrigation event, with each event occurring every 10 and 13 days in 2017 and 2018, respectively. At the end of the treatment, a total of 90.4 mm and 98.0 mm of water were used for irrigation by the SDI system, in 2017 and 2018 respectively.

The SICE water supply was continuous, and thus the emitter discharge changed continuously during the irrigation process (Fig. 3). This resulted in similar irrigation amounts for the three SICE treatments of approximately 104 mm in 2017 and 84 mm in 2018. The initial emitter discharge of SICE was relatively large, and gradually decreased in a generally stable manner, with slight fluctuations. These fluctuations in emitter discharge may be attributed to variations in soil moisture.

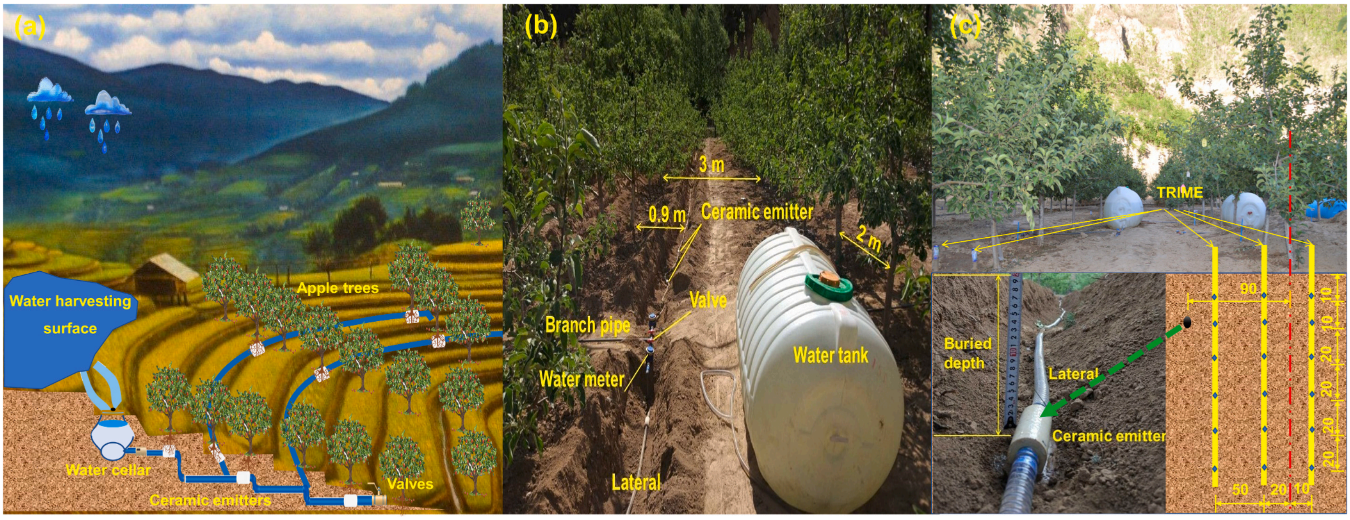

Fig. 2. Schematic of a typical subsurface irrigation system with ceramic emitters (a); SICE system used in this experiment (b); and the location of the access tubes (c). Note: the trench where the lateral and ceramic emitters were placed was filled in after the photograph was taken.

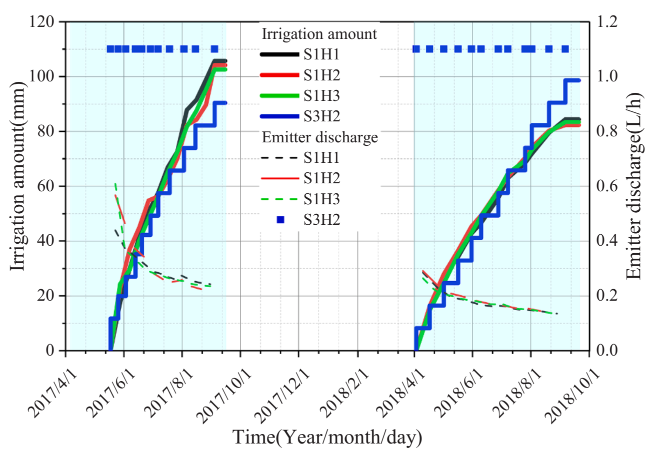

Fig. 3. Irrigation application process during the apple growing seasons of 2017 and 2018.

2.4. Field sampling and testing methods

2.4.1. Meteorological data

A weather station was set up at the test site to record daily meteorological variables automatically, such as temperature, humidity, wind speed, light, solar radiation, and air pressure over the entire growing period of the apple trees. Precipitation was recorded by a rain gauge installed on the weather station.

2.4.2. SWC, temperature and evapotranspiration (ET)

Soil water content and temperature at a depth of 0–100 cm were measured every 15 days after Stage I for each of the two growing seasons. More specifically, for each plot, *SWC* and temperature at depths of 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm were measured using a time-domain reflectometry (TDR) downhole sensor (TRIME-PICO-IPH, IMKO, Germany) after assessing the site-specific calibration equation. Three 120 cm long access tubes were installed at 10, 20 and 70 cm from the tree (Fig. 2**c**). A total of 18 *SWC* and temperature values across the soil profile were obtained for each measurement. Variations in average *SWC* over time for each growing season were determined as follows:

$$\sigma_{VA} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(VA_j - \overline{VA}\right)^2} \tag{1}$$

where σ_{VA} (%) is the standard deviation of VA_j, VA_j is the average *SWC* in the soil profile of *j*th measurement and $j = 1\ldots N$, N is the total measurement in the apple growth season, and $\overline{VA}$ is the average *SWC* over the entire apple growth period.

The soil water storage (*W*) in the soil profile (0–100 cm) throughout each of the growing seasons prior to Stage I and after Stage IV was then calculated as:

$$W = \sum_{i=1}^{6} V_i \times SD_i \tag{2}$$

where SD_i is soil depth (mm) at each soil layer and $i = 1\ldots6$.

Evapotranspiration was calculated using the soil water balance equation as follows:

$$ET = I + P + U + W_0 - W_1 - D \tag{3}$$

where *ET* (mm) is evapotranspiration, *I* (mm) is the irrigation amount, *P* (mm) is effective precipitation, which is measured using an automatic weather station at the experimental site, *U* (mm) is groundwater recharge (which was ignored in this study as the groundwater table was deeper than 50 m), *D* (mm) is the deep percolation, which is determined by subtracting the water above the field capacity from the total soil water in the root zone, and W_0 and W_1 are the soil water storage before Stage I and after Stage IV, respectively.

2.4.3. New shoot length (LNS), Yield, water use efficiency (WUE) and irrigation water use efficiency (IWUE)

Information about the growth of new shoots is an important morphological indicator for the construction and management of orchards. The growth of new shoots ensures the occurrence of photosynthesis for apple trees and promotes root growth (Castillo-Llanque and Rapoport, 2011). At the beginning of this experiment, three apple trees within each treatment were randomly selected, and four different shoots, growing in four different directions, were measured. The new shoot length was taken as the average value of these 12 measurements.

The produce from apple trees in each treatment was weighed immediately after harvesting. Three plants within each plot were randomly selected at harvest to determine seed yield. *WUE* was defined as:

$$WUE = \frac{Y}{ET} \tag{4}$$

where WUE (kg m^{-3}), Y (t ha^{-1}), and ET (mm) are the water use efficiency, yield, and evapotranspiration of the apple tree, respectively. From this, $IWUE$ (kg m^{-3}) was subsequently defined as follows:

$$IWUE = \frac{Y}{I} \tag{5}$$

3. Results and discussion

3.1. Meteorological conditions

Fig. 4a shows the daily precipitation and air temperature over the apple growing seasons of 2017 and 2018. Air temperatures exhibited a similar trend for both years. An extreme weather event occurring on April 7, 2018 resulted in marked temperature changes for the 2018 growing season (Fig. 4b). A minimum air temperature of − 5.6 °C was measured across the whole growing season, yet the minimum air temperature was higher than 0 °C from 28 March to 6 April, 2018. In traditional Chinese culture, this phenomenon is known as "the late spring coldness". Despite similarities in annual precipitation between the 2017 (456.4 mm) and 2018 (487.8 mm) growing seasons, the temporal precipitation distribution differed. Some 23.0–24.6% (104.9–119.8 mm) of the total precipitation occurred during Stages I and II (approximately 87 days) for both years, limiting the amount of water received by the apple trees to 1.4 mm per day. In these conditions, drought stress can ensue for apples that depend solely on precipitation for their water (Zhang et al., 2019). In 2017, approximately 76.9% (351.1 mm) of precipitation occurred during Stage III, while 51.3% (250.2 mm) was recorded for the same stage in 2018. During Stage IV, just 0.4 mm of precipitation was recorded for 2017, while 117.8 mm was recorded for 2018.

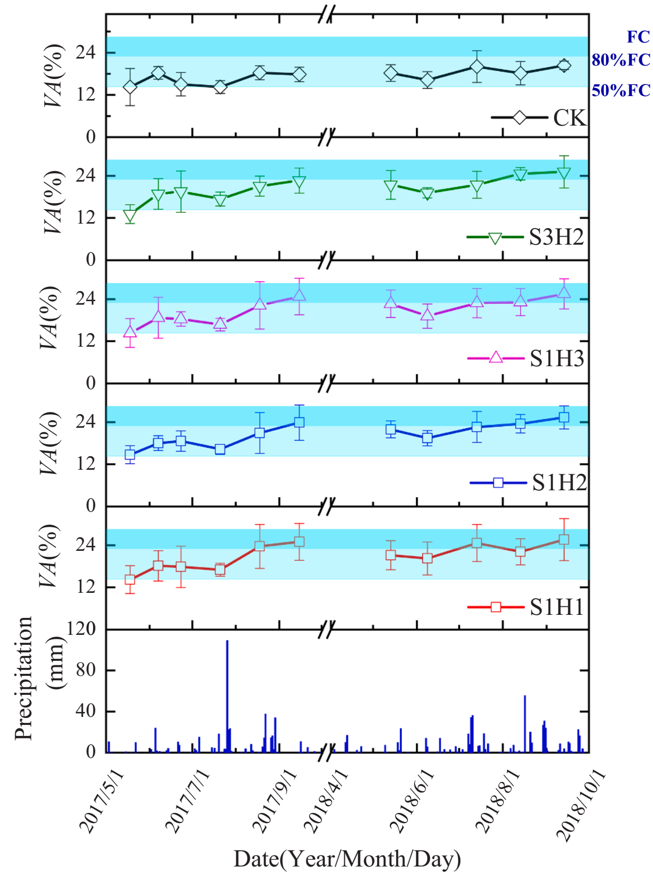

Fig. 5. Average soil water content (*VA*) trend with time. Error bars indicate standard deviation of mean, n = 18.

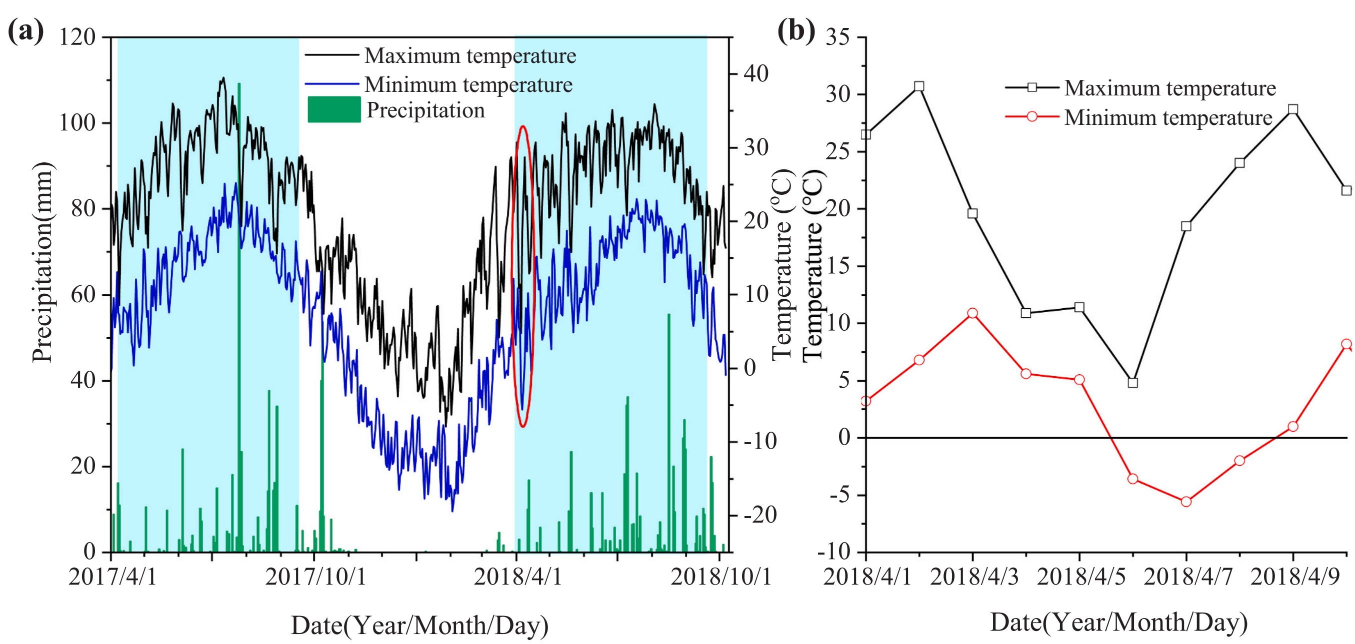

Fig. 4. Variation in daily temperature and precipitation during the 2017 and 2018 apple tree growing seasons at the experimental site (data collected on 1 April 2017 and 1 October 2018) (a); Daily temperatures between April 4–10, 2018 at the experimental site (b).

3.2. Effect of meteorological conditions and irrigation on SWC and temperature

Fig. 5 shows the temporal dynamics of the average *SWC* (*VA*) and corresponding standard deviations for 2017 and 2018. SICE and SDI were observed to increase the *SWC* significantly ($p < 0.05$) around the root of the apple trees compared to the CK treatment. The $\overline{VA}$ of S1H1, S1H2 and S1H3 were measured as 19.3%, 18.7% and 19.2% in 2017, respectively. These values are close to that of S3H2 (18.8%) and higher than that of CK (16.3%). However, the precipitation in 2018 had a strong impact on *SWC* due to the uniform distribution of precipitation over time. In particular, the $\overline{VA}$ of CK, S1H1, S1H2 and S1H3, S3H2 were measured as 18.6%, 22.7%, 22.6%, 22.7% and 22.3% in 2018, respectively. These values are much higher than those of 2017. The changes in *SWC* (σ_{VA}) of S1H1, S1H2, S1H3 and S3H2 in 2017 were calculated as 3.07%, 2.10%, 2.57% and 2.71%, respectively, all of which were much bigger than those of CK (1.87%). In addition, the *SWC* for SICE and SDI were maintained between 55% and 80% of field capacity (FC). In 2018, the σ_{VA} of CK, S1H1, S1H2, S1H3 and S3H2 were 1.51%, 2.04%, 1.96%, 2.03% and 2.21%, respectively. In particular, the σ_{VA} of the CK was smaller than those for SDI and SICE. However, σ_{VA} of S1H1 was bigger than that of S3H2 because of the concentrated precipitation in 2017. The σ_{VA} value of the other SICE treatments are all smaller than that of S3H2, which indicates that the changes in *SWC* for SICE are more uniform. This is mainly because SICE is a continuous irrigation method while SDI is an intermittent irrigation method, and thus variations in *SWC* are different between the two. SICE can be considered as a very high-frequency irrigation method. Ayars et al. (1999) concluded that the use of high-frequency SDI produced a smaller wetted soil volume and maintained a higher mean *SWC* compared to low-frequency SDI. The SICE system allows for the real-time replenishment of soil moisture, hence, in our experiment, the *SWC* in the apple orchard remained relatively stable with values spanning a suitable range.

To understand further the effect of irrigation on *SWC*, the soil water distribution of the five treatments at different stages in 2017 is shown in Fig. 6. During Stage I, prior to irrigation (May 5, 2017), the *SWC* of the five treatments was observed to be low with a relatively uniform distribution. The surface *SWC* was low, while the *SWC* in deeper layers was slightly higher. The *SWC* of the five treatments was generally 0.04–0.22 $cm^3\ cm^{-3}$, with no significant differences ($p = 0.145 > 0.05$). In addition, the CK treatment exhibited the highest *SWC*.

During Stage II, 42 days after irrigation started (28 June, 2017), significant differences were observed in the *SWC* between the five treatments ($p = 0.033 < 0.05$). For an irrigation tape depth of 20 cm,

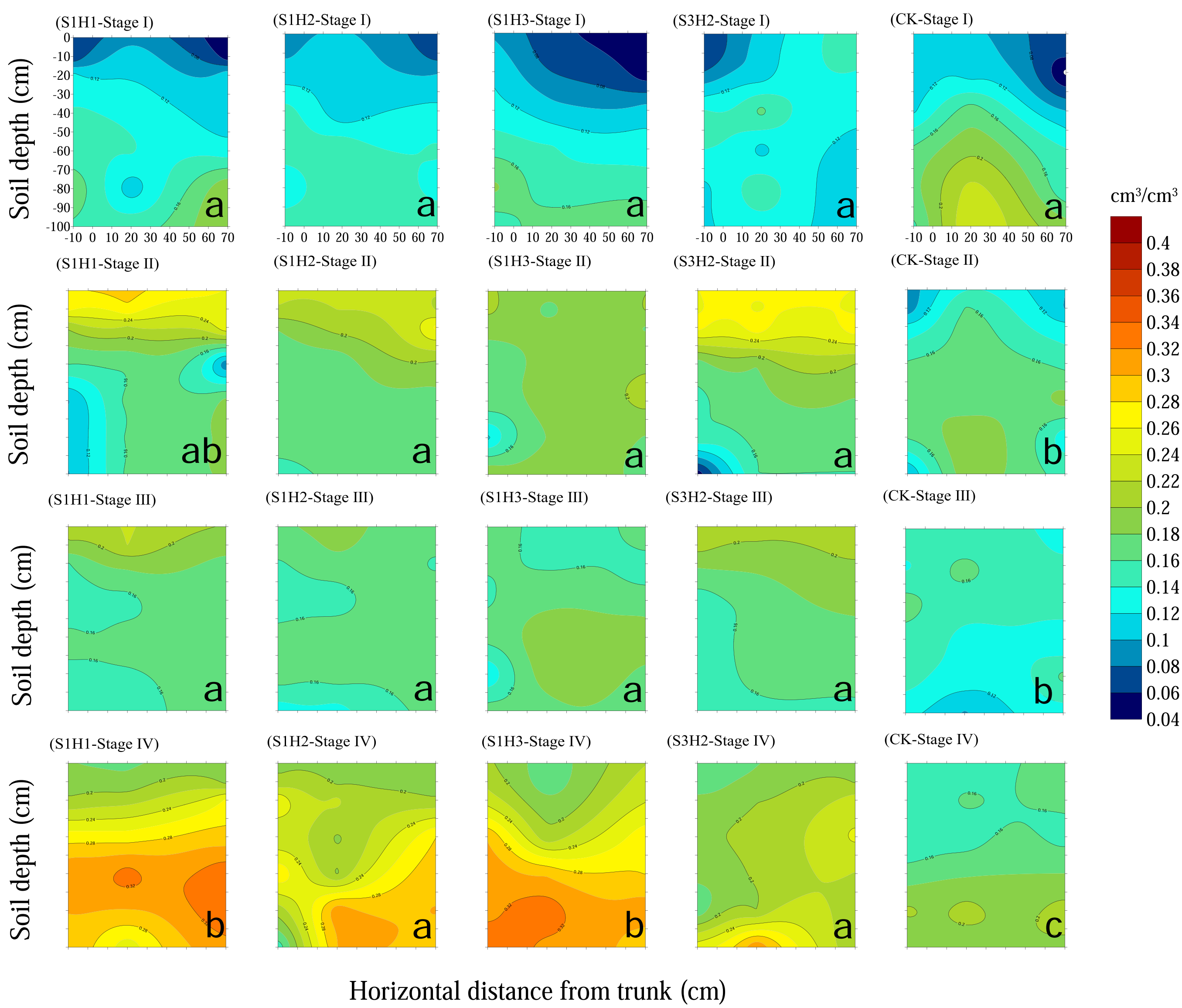

Fig. 6. Soil water distribution of the 5 treatments at Stages I–IV. a, b and c indicate significant differences ($p < 0.05$) between the five treatments (2017).

the water moved upwards to maintain the surface soil moisture at a high level (0.24–0.30 cm^3 cm^{-3}), resulting in insufficient moisture in the lowest soil profile layer. At irrigation tape depths of 40 cm and 60 cm, the soil water distribution was relatively uniform, with a higher *SWC* in the surface layer and a slightly lower value in the bottom layer (0.26 and 0.16 cm^3 cm^{-3}, respectively).

During Stage III, 64 days after irrigation started (21 July, 2017), and following a long period of drought, the soil moisture status reached its poorest state over the entire growing season, with the irrigation treatments demonstrating a more favorable soil moisture environment compared to that without irrigation ($p = 0.000 < 0.05$). For CK, the overall *SWC* was below 0.16 cm^3 cm^{-3}. Such low levels of soil moisture over the entire root zone are not conducive to the growth of apple trees. The irrigation measures clearly improved the soil moisture status.

During the later periods of Stages III and IV for 2017, significant differences were observed in the *SWC* between the five treatments ($p < 0.05$). In addition, the *SWC* was high, and exceeded field capacity for S1H1. Such conditions are unfavorable for apple growth. Therefore, measures such as film mulching or drainage are required to limit the influence of precipitation.

Precipitation and irrigation are the main sources of soil moisture (Song et al., 2020). For both years, less precipitation from May to early July (dry season) than over the rest of the year (Fig. 4). During these months, the apple trees consumed a large quantity of water, thus the *SWC* over this period was relatively low. CK *VA* values were greatly reduced (from 18.3% to 14.3%) due to the continuous drought in July. In particular, the minimum *VA* value (14.3%) was 50% lower than the FC. However, the SICE and SDI *VA* values were much higher than those of CK due to the applied irrigation treatments. The Loess Plateau entered the rainy season in mid-July, and the *SWC* in the apple orchards rapidly increased (4–8%), having a positive effect on the growth of apple trees. During Stage IV of 2018, a large amount of precipitation resulted in a much higher *SWC* compared to that of 2017. During Stage IV in 2017, precipitation was 0.4 mm, and thus a large amount of irrigation water quickly entered the soil, maintaining the *SWC* at a high level. However, during Stage IV in 2018, there was 117.8 mm of rain. This large amount of precipitation over a short time during 2018 resulted in a rapid increase in *SWC*. Such a phenomenon is detrimental to apple color and can cause water stress, which can subsequently impair the growth of apple trees. Although precipitation has obvious temporal and spatial inhomogeneity, the soil moisture environment in the root zone was still maintained in a better condition under irrigation. At present, there are many methods employed to maintain the soil moisture content within a more suitable range (Nam et al., 2020), for example, the real-time transmission of data through soil moisture or weight sensors to control valve switching. Distinct from these two methods, SICE is an effective irrigation method that does not rely on soil sensors and can maintain the *SWC* at a relatively stable level.

As shown in Fig. 4b, temperatures were high during the early period of Stage I, peaking above 30 °C, resulting in the blooming and sprouting of the apples. However, on April 6, the temperature suddenly dropped below 0 °C for three days, increasing the risk of frost damage to apple trees and flowers. Fig. 7 shows the soil temperature of five treatments on April 12, 2018. The average soil temperatures of S1H1, S1H2, S1H3 were recorded as 18.6 °C, 17.6 °C and 17.2 °C, respectively, all of which were much higher than that of CK (16.3 °C) and S3H2 (16.2 °C). More specifically, with irrigation, the soil water distribution is altered, increasing the soil specific heat capacity, which consequently delays the effect of changes in the air temperature on soil temperature. Low temperatures can happen without warning and are generally unpredictable. However, SDI, an intermittent irrigation method, cannot maintain a relatively high *SWC* for a long time, so does not maintain soil temperature as well when there is low *SWC* and low temperatures. SICE is different from SDI because it provides a continuous water supply, keeping *SWC* at a high level and adapting to sudden low temperatures. Therefore, this irrigation method is better than SDI because it helps

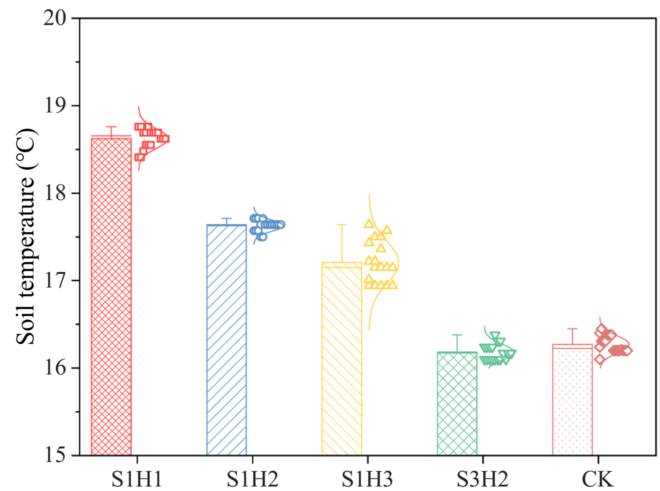

Fig. 7. Soil temperature of five treatments in April 12, 2018.

maintain a more suitable soil temperature when the cold spring temperatures occur. This also means that SICE is more adaptable than SDI to changing climate.

3.3. Effect of meteorological conditions and irrigation on apple growth

The lengths of the new shoots (*LNS*) at the end of the shoot growing stage (August 7 in 2017, and August 12 in 2018) are shown in Fig. 8. *LNS* was significantly different between the different treatments in 2017, yet no significant effects were observed for new shoot length change in 2018. More specifically, *LNS* values of the SICE and SDI treatments were greater than those of CK, yet no significant differences were observed between irrigation treatments. The *LNS* value of S1H2 (37.1 cm) was the largest, followed by S1H1, with S1H3 significantly lower than S1H2 and S1H1. This may be attributed to the buried depth of SICE (60 cm), which allows the irrigation water to move towards deeper soil layers, preventing sufficient uptake of water by the shallow layer roots and thus limiting new shoot growth. *LNS* values in 2018 were lower than those of 2017, which may be linked to the limited apple shoot growth due to the lower temperature in Stage I of 2018. The *LNS* growth rate of the S1H1, S1H2, S1H3, S3H2, and CK treatments were calculated as 4.18 mm/d, 5.48 mm/d, 3.45 mm/d, 3.57 mm/d, and 2.23 mm/d in 2017, respectively. The values for the SICE treatments were significantly greater than

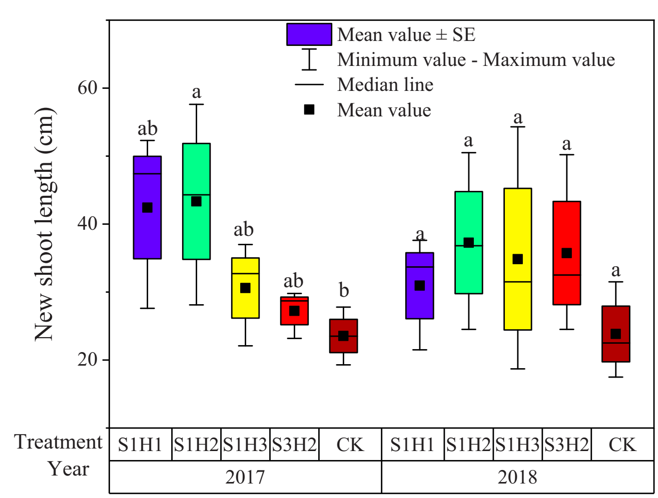

Fig. 8. New shoot length of apple trees at the end of the growing period for different treatments in 2017 and 2018. Bars indicate standard deviation of mean, n = 12.

those of the CK treatment, and almost equal to those of the SDI treatment.

Table 3 shows the apple yield, *ET*, *WUE* and *IWUE* determined for the different treatments in 2017 and 2018. As expected, apple yield was significantly ($p < 0.05$) affected by the irrigation method and the SICE buried depth across the two growing seasons. Using irrigation, apple production increased significantly. The S1H2 treatment exhibited the maximum yield, increasing significantly by 90.4% and 68.6% compared with CK in 2017 and 2018, respectively. However, the yield-increasing effect between the two irrigation methods differed. For both years, significant differences were observed in apple yields between S1H1, S1H2 and S1H3 under the same meteorological conditions with different buried depths. A greater amount of irrigation water was lost by surface evaporation under S1H1, while for S1H3, more irrigation water was lost due to deep percolation. Consequently, the water lost by these processes failed to be absorbed by the roots, reducing the *IWUE* compared to S1H2. The *IWUE* value in 2017 was lower than that of 2018, as a result of the smaller amount of irrigation water used for the latter. The SICE treatments were associated with an increase in water consumption compared with CK, as well as a rise in apple production. Over the two growing seasons, the apple trees irrigated using the SICE and SDI treatments consumed greater amounts of water (*ET*) and exhibited a higher *WUE* compared to those of the CK treatment. The *ET* values of S1H1, S1H2 and S1H3 were higher than those of CK by 10.0% (46.6 mm), 9.9% (46.1 mm) and 11.2% (52.3 mm), while the *WUE* in S1H1, S1H2 and S1H3 was 55.7% (1.70 kg/m^3), 60.7% (1.85 kg/m^3) and 41.0% (1.25 kg/m^3) higher than the control, respectively. In addition, the S3H2 *ET* and *WUE* values were 13.1% (61.3 mm) and 45.9% (1.40 kg/m^3) greater than those of CK, respectively. The S3H2 *ET* was also significantly higher than those of the SICE treatments (2.8% and 13.0 mm), while the *WUE* was lower than that of S1H1 and S1H2 (9.8% and 14.8%, respectively), but higher than that of S1H3 (4.9%). Note that the maximum *IWUE* was observed for the S1H2 treatment (26.75 kg/m^3), which was 7.7% (2.10 kg/m^3), 13.1% (3.50 kg/m^3) and 6.5% (1.75 kg/m^3) higher than those of S1H1, S1H3 and S3H2, respectively.

Meteorological conditions such as temperature, light and precipitation are important factors influencing apple plant growth, fruit dry matter accumulation and water consumption. Zhang et al. (2018) found that the average, maximum and minimum temperatures, and the percentage of sunshine from April to October, as well as annual total precipitation and annual average temperature, all had a positive effect on fruit quality. In our experiment, precipitation was observed to be the main meteorological factor affecting fruit tree yields. The precipitation levels in Stages I and II had the greatest impact on apple growth and final yield. Precipitation in the Loess Plateau is generally lower from January to mid-July compared to the rest of the year (Fig. 4). This corresponds to Stages I and II of apple growth. During Stage I of 2017, precipitation reached just 51.7 mm, except for four occasions with precipitation at 9.7 mm or more, and seven occasions with precipitation less than 5 mm (and thus regarded as insignificant). During Stage I of 2018, precipitation was observed to be slightly higher than 2017 at 54.6 mm. The average daily precipitation was equivalent to 1 mm/d for the initial 50 days of the growing season for both years. At this level, meeting the water requirements of the apple trees was a challenge. The average precipitation during Stage II was approximately 1.44 mm/d and 1.76 mm/d in 2017 and 2018, respectively. At this stage, apple trees generally exhibit rapid growth and consume large amounts of water. Thus, solely depending on precipitation to meet the water consumption of the apple trees results in drought stress. Precipitation increased during Stages III and IV, allowing for the replenishment of soil moisture. Furthermore, *SWC* increased rapidly, and even exceeded FC, due to the occurrence of a short but intense rainstorm. During Stage IV, sunny days are required to ensure that apples ripen, changing from green to red. These observations indicate that, in the Loess Plateau, irrigation should be carried out from April to June, while from July to September, appropriate drainage measures should be taken.

A suitable irrigation frequency helps to optimize soil moisture and thereby increases yield and *WUE* (Zhang et al., 2019). Boyle et al. (2016) found that leaf water potential and leaf xylem abscisic acid levels were more attenuated with frequent irrigation (daily) than with infrequent irrigation (every 4 days). These physiological changes correspond to differences in plant production, with frequently irrigated plants having a greater shoot fresh weight (18%) compared to infrequently irrigated plants. Fan et al. (2019) discovered that high-frequency irrigation (16 irrigation events with 375 mL per plant for each event) could achieve high yields and increase quality for organic melon. Stallmann et al. (2018) concluded that a lower irrigation frequency had negative effects on *WUE* and the grain yield of spring wheat. Nam et al. (2020) found that maintaining *SWC* at a constant level promoted a higher yield and quality than a fluctuating *SWC* did. In our study, the value of σ_{VA} for SDI exceeds that of S1H2 (Fig. 5), implying a possibly smaller yield of S3H2 compared to S1H2. However, the S3H2 yield was 7.2% higher than that of S1H3 for the two growing seasons, and 1.6% and 7.6% lower than those of S1H1 and S1H2, respectively. It was determined that SDI was generally effective in controlling the irrigation amount with the use of the upper and lower soil moisture content limits. However, the continuous irrigation method (SICE) could maintain *SWC* in a suitable range for apple growth. Fentabil et al. (2016) found that irrigation every second day reduced area-scaled N_2O emissions by 27% compared with irrigation every day. Therefore, selecting a reasonable irrigation frequency not only affects the growth of fruit trees, but also affects greenhouse gas emissions. In the future, the greenhouse gas emissions of apple trees using SICE need to be studied.

Cold stress adversely affects plant growth and development (Zhu, 2016). The effect of extreme weather on the plant metabolism arises from the inhibition of metabolic enzymes due to the freezing of the fruit buds and flowers (Chinnusamy et al., 2007; Guo et al., 2019). This can cause irreversible damage, greatly reducing apple yield. The use of irrigation measures in our experiment reduced the negative impact on yield following an extreme weather event because of the maintenance of soil temperature. In the Loess Plateau, the sustainability of the apple industry may be undermined by an uneven precipitation distribution and a scarcity of water. SICE with a suitable buried depth is an effective method that can potentially provide a suitable soil water and temperature environment for apple trees, thus ensuring apple growth.

4. Conclusions

The SCIE system could effectively increase soil water content in the 0–100 cm soil layer, and keep the soil water content at a relatively stable

Table 3
Yield, water consumption, water use efficiency and irrigation water use efficiency for different treatments over the 2017 and 2018 growing seasons.

Index	2017					2018				
	CK	S1H1	S1H2	S1H3	S3H2	CK	S1H1	S1H2	S1H3	S3H2
ET (mm)	469.0c	476.5b	507.2a	473.5bc	511.3a	465.4e	551.1b	519.4d	565.4a	545.7c
Yield (t ha^{-1})	15.75d	28.86ab	29.99a	26.22c	27.83bc	12.45d	18.63bc	20.31a	17.40c	18.93b
WUE (kg m^{-3})	3.4c	6.1a	5.9ab	5.5ab	5.4b	2.7d	3.4bc	3.9a	3.1c	3.5b
IWUE (kg m^{-3})	–	27.3b	28.8b	25.6b	30.8a	–	22.1b	24.7a	20.9bc	19.2c

a, b, c and d indicate significant differences ($p < 0.05$) between the five treatments.

and within a suitable range during the growth period of apple trees. For a SICE buried depth of 40 cm, the *LNS,* yield*, WUE* and *IWUE* were 15.9%, 7.6%, 14.8% and 6.5% higher respectively than SDI. SICE significantly enhanced yield through its ability to save water and increase soil temperature for apple trees. Therefore, SICE could not only provide a suitable soil water environment and ensure the stable growth of apple trees, but also reduce frost damage to apples. A suitable buried depth of SICE for apple trees in the Loess Plateau is 40 cm. Further field experiments are required to study the effect of SICE on soil quality and greenhouse gas emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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