

Full Length Research Paper

## Scheduling irrigation for jujube (*Ziziphus jujuba* Mill.)

Ping Zhang<sup>1,2</sup>, You-Ke Wang<sup>1\*</sup>, Jing-Wu Zhan<sup>2,3</sup>, Xing Wang<sup>1</sup> and Peng Wu<sup>2,3</sup>

<sup>1</sup>Northwest A&F University, Yangling 712100, P.R. China.

<sup>2</sup>Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling Shaanxi 712100, P.R. China.

<sup>3</sup>Graduate School of Chinese Academy of Sciences, Beijing 100049, P.R. China.

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This study was performed to select suitable indicator for scheduling the irrigation of jujube (*Ziziphus jujuba* Mill.) grown in the Loess Plateau. The relationships between plant-based indicators and soil matrix potential as well as meteorological factors of jujube under deficit irrigation compared with well irrigation were determined. The results showed that maximum daily trunk shrinkage increased and maximum daily trunk diameter, gas conductance and midday leaf water potential decreased in response to higher and lower soil matrix potential, respectively. However, the maximum daily trunk shrinkage signal intensity to noise ratio was highest in response to higher and lower soil matrix potential. Besides, the maximum daily trunk shrinkage correlated well with reference evapotranspiration and vapor pressure deficit ( $r^2 = 0.702$  and  $0.605$  respectively). When the soil water potential was greater than  $-25\text{kPa}$  or less than  $-40\text{kPa}$ , maximum daily trunk shrinkage values showed increasing trend, suggesting that Jujube might be subject to water stress. Based on this, the suitable soil water potential values of pear-jujube in anthesis and setting periods were identified between  $-40\text{kPa}$  and  $-25\text{kPa}$  and the values can conduct precise irrigation of jujube in the Loess Plateau.

**Key words:** Water stress, water status indicators, soil water potential, Jujube (*Ziziphus jujuba* Mill.), anthesis, fruit setting periods.

### INTRODUCTION

Agricultural production security, as one of the global problems, bothers the entire world, yet the portion of fresh water currently available for agriculture (72%) is decreasing (Cai and Rosegrant, 2003), not only in arid and drought prone areas but also in regions where rainfall is abundant: water scarcity concerns the quantity of resource available and the quality of the water because degraded water resources become unavailable for more stringent requirements (Pereira et al., 2002).

In the Loess Plateau of China, Jujube (*Ziziphus jujuba* Mill.) is an ancient economic forest tree species with a drought resistance characteristic. For thousands of years, there is almost no irrigation of jujube and farms have not detected the trees' death caused by drought. Jujube shows a good or lean harvest depending on the amount of annual rainfall. Our survey showed that the multi-year

average yield of jujube was only  $0.50\text{Mgha}^{-1}$  in northern Shaanxi (Wu et al., 2008). In recent years, micro-irrigation of jujube on sloping land has been practiced in Mengcha village, Mizhi county for three years and productivity had been up to  $1.98\text{Mgha}^{-1}$  (Wu et al., 2008). This fact clearly indicates that high-yield is still guaranteed by good irrigation although jujube does not die easily because of its drought resistance. However, due to its traditional nature, there is a lack of systematic and detailed studies of jujube water requirements.

Suitable determination of an appropriate soil matrix potential depends on an indicator which can reflect water content accurately, timely, as well as with minimal variation among trees (Fernández et al., 2001; Alarcón et al., 2003; Goldhamer et al., 1999). The research about water information indicators has changed from merely the consideration of soil moisture to also plant-based indicators which are sensitive to soil moisture. Many researchers have studied appropriate indicators for plants, such as lemon (Ortuño et al., 2006; García-Orellana et al., 2007), cotton (Zhang et al., 2006), almond

\*Corresponding author. E-mail: [sdauzhangping@yahoo.cn](mailto:sdauzhangping@yahoo.cn), [gjzwyk@vip.sina.com](mailto:gjzwyk@vip.sina.com). Tel: 13359180956. Fax: 02987010700.

**Table 1.** Tree sizes and the sensors of measuring trunk diameter fluctuation in the experiment.

Tree number	TDF sensor number	Trunk diameter (cm)	Tree height (cm)	Tree canopy radius (cm)
1-1	DD-755	2.552 <sup>a</sup>	74.89 <sup>a</sup>	26.51 <sup>a</sup>
1-2	DD-754	2.585 <sup>a</sup>	74.96 <sup>a</sup>	26.62 <sup>a</sup>
1-3	DD-744	2.580 <sup>a</sup>	74.42 <sup>a</sup>	26.56 <sup>a</sup>
2-1	DD-752	2.573 <sup>a</sup>	74.86 <sup>a</sup>	26.50 <sup>a</sup>
2-2	DD-750	2.521 <sup>a</sup>	74.64 <sup>a</sup>	26.41 <sup>a</sup>
2-3	DD-745	2.501 <sup>a</sup>	74.87 <sup>a</sup>	26.01 <sup>a</sup>

TDF is trunk diameter fluctuation. Same letters within a column indicate non-significant differences at  $p \leq 0.05$ .

(Nortes et al., 2005), peach (Marsal et al., 2002), cabbage (McBurney and Costigan, 1984) and apple trees (Doltra et al., 2007). The high moisture-sensitive indicators include trunk diameter fluctuation, leaf water potential or canopy temperature. Trunk diameter fluctuations are closely related to soil and plant water potentials (Klepper et al., 1971; Parlange et al., 1975; Simonneau et al., 1993). Furthermore, they can be easily determined continuously and with automatic recording which does not harm the plants. Daily maximum trunk diameter, daily minimum trunk diameter and maximum diurnal trunk diameter shrinkage can be calculated from trunk diameter fluctuations on a day to day basis. Trunk diameter fluctuations (Huguet et al., 1992; Cabibel and Isberie, 1997; Cohen et al., 2001; Ortuño et al., 2004b), leaf water potential (Peretz et al., 1984), predawn leaf water potential (Améglio et al., 1999) are all appropriate indicators for diagnosing plant water information, but it is troublesome to measure leaf water potential using a pressure chamber (Turner, 1981). It is also difficult to achieve automatic and continuous records with the pressure chamber.

Definition of threshold values of soil moisture for irrigation management, using plant water status ensures the maintenance of soil moisture conditions that avoid physiological stress. This approach is likely to be more sensitive than assessing differences in production (Thompon et al., 2007). Because plant status indicators change dynamically; this can reflect crops water status for the time of day, while production levels are less subject to variation. In addition, the threshold values obtained in agronomic studies may be influenced by other factors influencing crop yield and by the particular soil moisture tested (Thompon et al., 2007). Recent examination of the potential application of soil and plant sensors for irrigation scheduling have used plant water status to identify when crops initially experience water stress (Feres and Goldamer, 2003; Intrigliolo and Castel, 2004; Gallardo et al., 2006b). However, there is no report about suitable values of soil matrix potential for jujube. The aims of this study are to select an appropriate indicator for the diagnosis of jujube water needs by comparing sensitivity and stability of maximum diurnal

trunk diameter shrinkage, daily maximum trunk diameter, midday leaf water potential and gas conductance in response to soil matrix potential changes and define a suitable soil matrix potential of jujube during anthesis and fruit setting periods according to a relationship between the appropriate indicator and soil matrix potential.

## MATERIALS AND METHODS

### Site description and experiment design

A jujube demonstration zone was used, which was equipped with micro-irrigation on sloping land in Mengcha village (38.18°N

109.47°E, Mizhi County located in the hilly and ravine area of the Loess Plateau. The site is in a semi-arid zone. Mean annual precipitation is 393 mm, being mainly concentrated in the period from July to September. The soil type is loess with a uniform texture and moderate permeability. The mean bulk density was 1.29 g/cm<sup>3</sup> in the upper 1.0 m of the soil profile. Field capacity was an average of 23 in the upper 1.0 m of the soil profile (mass percentage). The initial soil water content was 10.8%, with a corresponding soil matrix potential of -50 kPa.

Three years old pear jujubes were selected as experimental trees. Similarly, the soil matrix potential corresponding to the soil water content was -33 kPa to -22 kPa in our study site. For the consideration of the water requirement of pear jujube in anthesis, fruit setting periods and field capacity values in the upper 1.0 m of the profile, two levels of water treatments (T0 and T1) were imposed on jujube trees. Control plants (T0) were well irrigate and maintained soil matrix potential between -33 kPa and -25 kPa. T1 plants were initially surface irrigated to produce a soil matrix potential corresponding with 90% of field capacity; thereafter irrigation was withheld, with soil matrix potential dropping naturally. In T1 plants, soil matrix potential had higher values of -10 kPa to -23 kPa, maintained at 15 days. Then in the next 9 days soil matrix potential was close to that of T0 and finally the plants were subjected to water deficit stress for 26 days. Each treatment occupied one plot measuring 6x1x1 m (length x width x depth) under a mobile rain shelter which could protect them from rainfall. The two plots were adjacent and there was a row of three trees planted in a plot and two trees were labeled for repetitions in time. Basic information for the sampled trees is shown in Table 1. The study site was equipped for drip irrigation. To ensure uniformity of irrigation there were two pipes, with each having four drippers evenly installed in each plot and each emitter discharged 4L/h. In the T0 treatment, irrigation timing was controlled automatically by a

water potential controlled irrigation system. When the soil matrix potential was below -33 kPa, information was sent to an electromagnetic valve to allow automatic irrigation for five minutes. Half an hour later, if the soil matrix potential was still lower than the set values, the above process was repeated, until the soil matrix potential was between -33 kPa and -25kPa.

### Soil matrix potential measurement

Soil matrix potential was measured using an equilibrium tensiometer (model EQ15 basic, range -1500-0kPa, accuracy  $\pm 10$ kPa, Ecomatik, Germany). Each plot had three soil matrix potential sensors at a depth of 30 cm; two of them were buried between the trees which were linked to a datalogger (model DL2e, Delta-T Devices, U.K.), and the other one was at 15 cm away from the middle tree which was connected to another datalogger (model GP1, Delta-T Devices, U.K.) to control irrigation automatically. Measurements were taken every 10s and the dataloggers were programmed to report 30min means.

### Indicators based-plant of jujube

Trunk diameter fluctuations were measured throughout the experimental period for each tree and treatment using a set of linear variable displacement transducers (LVDT) (model DF, range 0-11mm, accuracy  $\pm 7 \mu\text{m}$ , Ecomatik, Germany) attached to the trunk, with a special bracket made of Invar and aluminum. Sensors were placed on the north side and were covered with silver and thermoprotected foil to prevent wind, temperature and rain from affecting the devices. All the sensors were linked to a datalogger (model DL2e, Delta-T Devices, U.K.). Measurements were taken every 10 s and the dataloggers were programmed to report 30 min means. From measurements of trunk diameter fluctuation on a day to day basis, maximum daily trunk diameter (MXTD), minimum daily diameter (MNTD) and maximum daily shrinkage (MDS) could be calculated. MDS signal intensity, that is a standardized MDS (actual MDS / reference MDS) were calculated as described by Goldhamer and Fereres, (2004) and MXTD was also standardized.

Midday (12.00 h solar time) leaf water potential was measured, every three days, in two mature sun-exposed leaves per plant, using a water potential datalogger (model Wescor Psypro, range -0.05- -8MPa, accuracy  $\pm 0.03$  MPa, ELITechGroup Wescor, USA). Two leaves were selected, with a similar type of leaf to that used for midday leaf water potential, and were labeled for the measurement of gas conductance. It was also measured at midday, every 3 days, using a field portable porometer (model AP4, range 5.0 -1200  $\text{mmol m}^{-2} \text{s}^{-1}$ , accuracy  $\pm 20\%$  (800 - 1200  $\text{mmol m}^{-2} \text{s}^{-1}$ , Delt -T, U. K.). In this study, midday leaf water potential and gas conductance were standardized (T0/T1 or T1/T0) as well.

### Meteorological data

Meteorological data were collected each 30 min by a mini-weather station, type watchdog 2000 and located 2 km from the experiment site.  $\text{ET}_0$  and  $\text{VPD}_{\text{md}}$  were calculated using the Penman-Monteith equation (Allen et al., 1998).

### Statistic analysis

Tree size data are the mean values of triplicate measurements. All measured variates were first characterized by description statistics of SPSS11.5 (means and standard error of the mean). Based on this, the coefficients of variation were calculated. The significance of difference of all variates between both treatments was tested with

one-way ANOVA of SPSS11.5. The correlations between maximum diurnal trunk diameter shrinkage and meteorological factors were analyzed using Linear Fit of Origin in version 8.0. The level of significant difference was at 0.05.

## RESULTS

### The dynamic changes of soil matrix potential

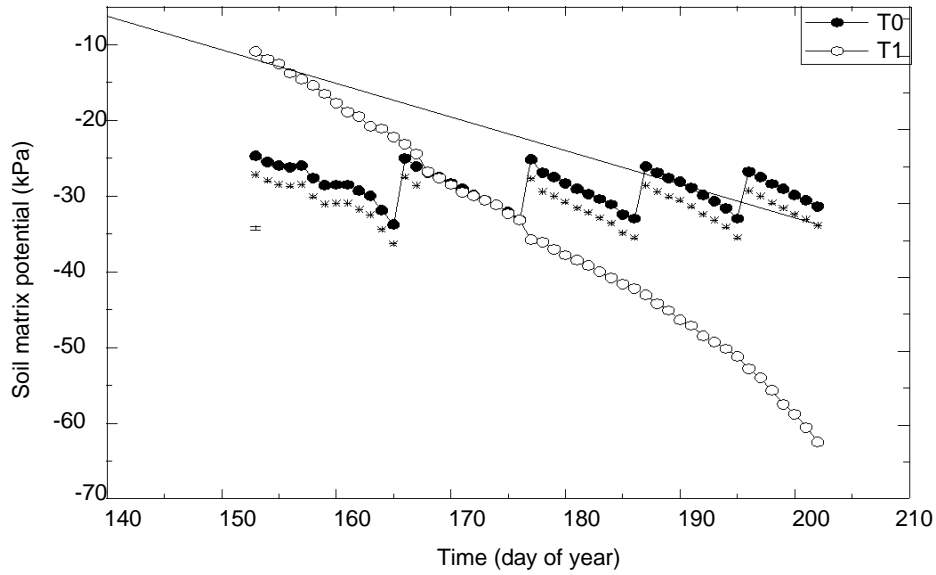
In the T0 treatment, irrigation was applied four times during the experiment. Soil matrix potential was nearly stable, in the range of -25 kPa to -33 kPa with a mean value of -28 kPa (Figure 1). However, the T1 treatment showed different responses. At the beginning, soil matrix potential was up to -10 kPa, thereafter, it showed a tendency to decrease naturally and reached a minimum value of -63 kPa. In the T1 treatment, soil matrix potential showed three stages compared to that of T0.

### Responses of plant-based indicators to the change of soil matrix potential

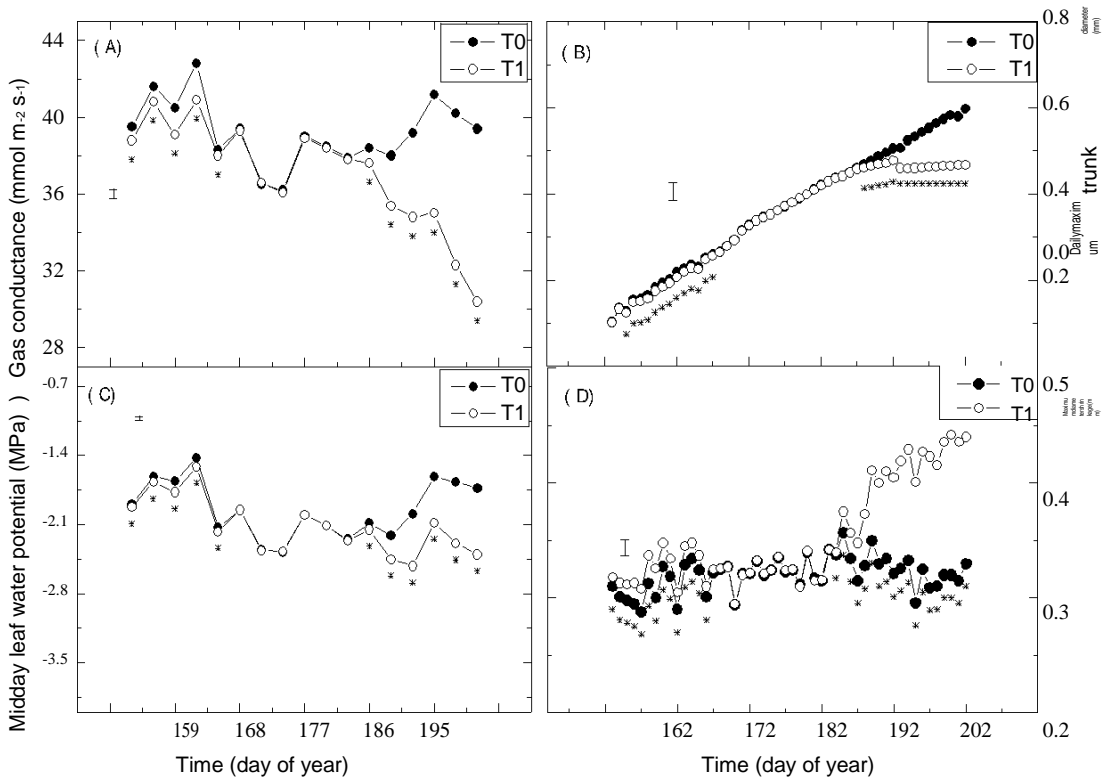
Midday leaf water potential and gas conductance in T0 plants were high and fairly constant during the experimental period, and reached mean value of -1.98MPa and 39.1  $\text{mmol m}^{-2} \text{s}^{-1}$ , respectively (Figures 2A and 2C). The higher soil matrix potential made these values fall slowly. Decreases in midday leaf water potential and gas conductance both became significant in the period from day 153 to 167 of year ( $P < 0.05$ ). The maximum differences between treatment values were -0.11MPa and 1.9  $\text{mmol m}^{-2} \text{s}^{-1}$ , on day 159 and 162 of year, respectively. As the soil matrix potential in T1 plants approached that of T0, midday leaf water potential and gas conductance in T1 plants increased compared to previous values and their significant differences between treatments disappeared from day 168 to 185 of the year ( $P > 0.05$ ). During the water deficit period, midday leaf water potential and gas conductance gradually decreased and both decreases became significant from day 186 onwards ( $P < 0.05$ ).

In T0 plants, MXTD increased continuously in the experimental period, with a mean growth rate of 0.01  $\text{mm d}^{-1}$  (Figure 2B). The higher soil matrix potential made MXTD values fall gradually and the decrease became significant from day 155 to 167 ( $P < 0.05$ ). With the decrease of soil matrix potential, MXTD growth rate increased to reach similar values of T0 plants from day 168 to 187. During the water deficit period, daily MXTD growth rate decreased again and showed significant differences between treatments from day 188 onwards ( $P < 0.05$ ).

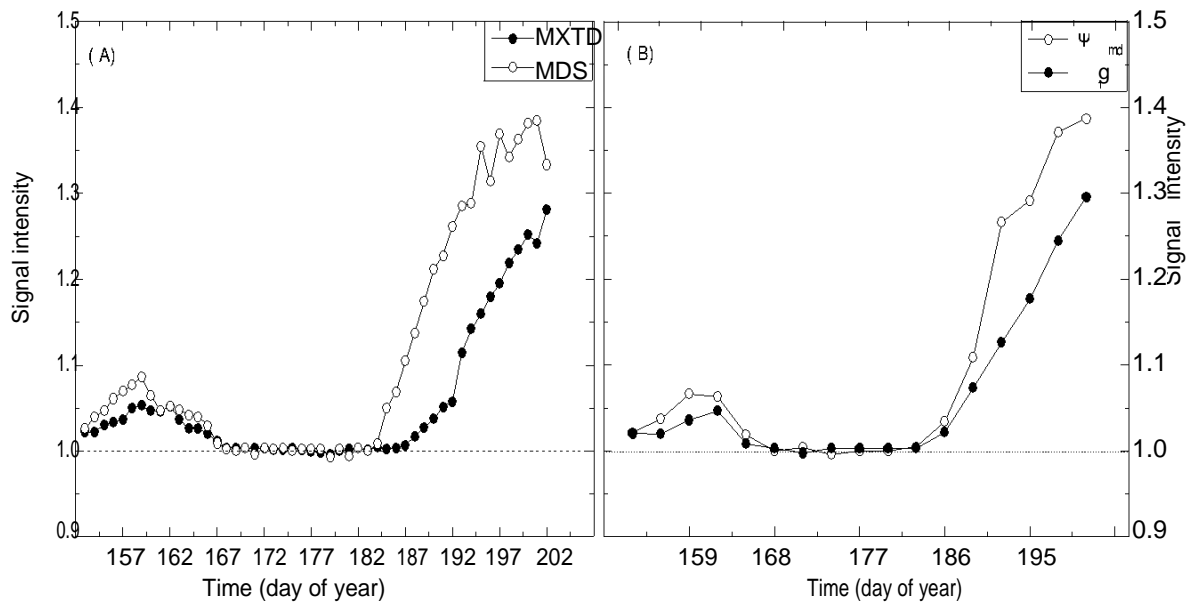
MDS in T0 plants remained stable and followed an increasing trend over the whole experiment period (Figure 2D). Differences between treatments were evident from day 153 to 166 of year ( $P < 0.05$ ) due to the increase in MDS in T1 plants under the higher soil matrix potential



**Figure 1.** Dynamic trends of soil water potential in T0 (closed symbols) and T1 (open symbols) during the measurement period from day of year 153 to 202. Vertical bar is twice the overall mean standard error (SE). Asterisks indicate statistically significant differences between treatments at  $P < 0.05$ . Each point is the mean of three values.



**Figure 2.** Dynamic trends of gas conductance (A), daily maximum trunk diameter (B), midday leaf water potential (C) and maximum diurnal trunk diameter shrinkage (D) in T0 (closed symbols) and T1 (open symbols) during the experiment period from day 153 to 202 of year. Vertical bar is twice the overall mean standard error (SE). Asterisks indicate statistically significant differences between treatments at  $P < 0.05$ . Each point is the mean of three values.



**Figure 3.** Dynamic trends of maximum diurnal trunk diameter shrinkage (MDS) (open symbols in A), daily maximum trunk diameter (MXTD) (closed symbols in A), midday leaf water potential ( $\Psi_{md}$ ) (open symbols in B) and gas conductance ( $g_1$ ) (closed symbols in B) signal intensities during the experiment from day 153 to 202. Horizontal line indicates the indicators signal intensity value of 1. Each point is the mean of three values.

**Table 2.** The responses of midday leaf water potential, gas conductance, daily maximum diameter and maximum diurnal trunk diameter shrinkage to higher soil matrix potential.

Indicators	Mean Signal Intensity	Mean Noise	Mean Signal Intensity/Mean Noise
MDS	1.05 <sup>a</sup>	0.054 <sup>a</sup>	19.4
$\Psi_{md}$	1.04 <sup>ac</sup>	0.058 <sup>b</sup>	17.90
$g_1$	1.03 <sup>bc</sup>	0.060 <sup>c</sup>	17.17
MXTD	1.03 <sup>c</sup>	0.064 <sup>d</sup>	16.10

$\Psi_{md}$  is midday leaf water potential;  $g_1$  is gas conductance; MXTD is daily maximum diameter; MDS is maximum diurnal trunk diameter shrinkage. Different letters within a column indicate significant differences at  $p < 0.05$ .

condition. Thereafter, with the soil matrix potential in T1 close to that of T0, MDS decreased progressively and showed similar values to T0 plants from day 167 to 183. From day 184 onwards, differences between treatments were evident ( $P < 0.05$ ) due to the increase in MDS in T1 plants under lower soil matrix potential conditions.

The signal intensity variations are shown in Figure 3, from which it was noted that they showed different degrees of response to the higher and lower soil matrix potential. MXTD and gas conductance responded slower than that of midday leaf water potential and MDS. The four indicator signal intensities all decreased to reach the value 1.0 and this value was maintained for different times due to the soil matrix potential in T1 treatment being close to that in T0 treatment. Water deficit induced midday leaf water potential, gas conductance, MXTD and

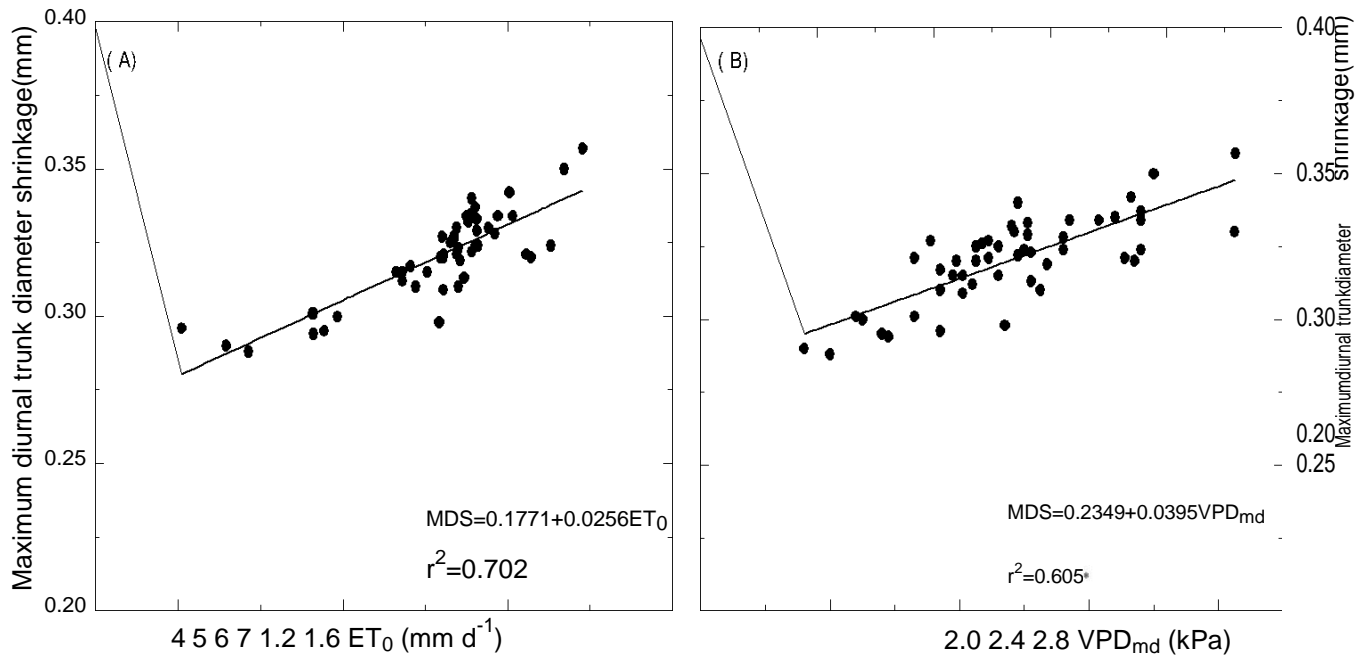
MDS signal intensity increased, which began to rise above the value of 1.0 on days 186, 186, 187 and 184, respectively.

To take into consideration the changes which occurred in plant water status during a short period of time when soil moisture changed (Ortuño et al., 2006), signal intensity and noise (coefficient variation) were analyzed for all indicators of high soil matrix potential from day 153 to 167 of year and low soil matrix potential from day 184 to 202. Data in Tables 2 and 3 indicate that the MDS mean signal intensity was higher than that of gas conductance and MXTD was similar to that of midday leaf water potential. The MDS mean noise was the lowest in response to both higher and lower soil matrix potential. The maximum diurnal trunk diameter shrinkage signal intensity to noise ratio was the highest, indicating that

**Table 3.** The responses of midday leaf water potential, gas conductance, daily maximum diameter and maximum diurnal trunk diameter shrinkage to lower soil matrix potential.

Indicators	Mean signal intensity	Mean noise	Mean signal intensity to mean noise ratio
MDS	1.25 <sup>a</sup>	0.053 <sup>a</sup>	23.80
$\Psi_{md}$	1.24 <sup>a</sup>	0.059 <sup>b</sup>	21.02
$g_1$	1.16 <sup>bc</sup>	0.061 <sup>c</sup>	19.02
MXTD	1.12 <sup>c</sup>	0.065 <sup>d</sup>	17.20

$\Psi_{md}$  is midday leaf water potential;  $g_1$  is gas conductance; MXTD is daily maximum diameter; MDS is maximum diurnal trunk diameter shrinkage. Different letters within a column indicate significant differences at  $p < 0.05$ .



**Figure 4.** The relationships between maximum diurnal trunk diameter shrinkage in T0 plants and ET<sub>0</sub> (A), VPD<sub>md</sub> (B) during the measurement period. The coefficients are statistical significance at  $P < 0.05$ .

maximum diurnal trunk diameter shrinkage was more sensitive than the other indicators in the diagnosis of the pear jujube water status in our experimental conditions.

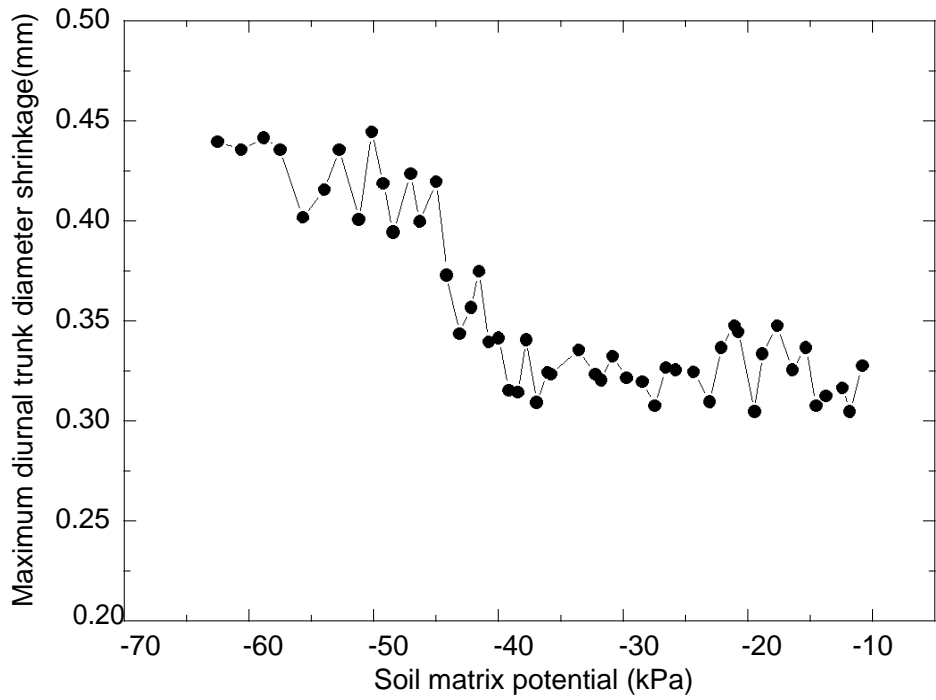
### Relationships between trunk diameter fluctuations and meteorological factors

To measure the effect of meteorological factors on MDS, correlations were determined between MDS and ET<sub>0</sub> as well as VPD<sub>md</sub> using measurement data of pear jujube in T0 treatment (from day 153 to 201 of year). Data in Figure 4 shows that MDS and ET<sub>0</sub> as well as VPD<sub>md</sub> were positively correlated ( $r^2 = 0.702$ ,  $0.605$  respectively,  $P < 0.05$ ) (Figures 4A and 4B).

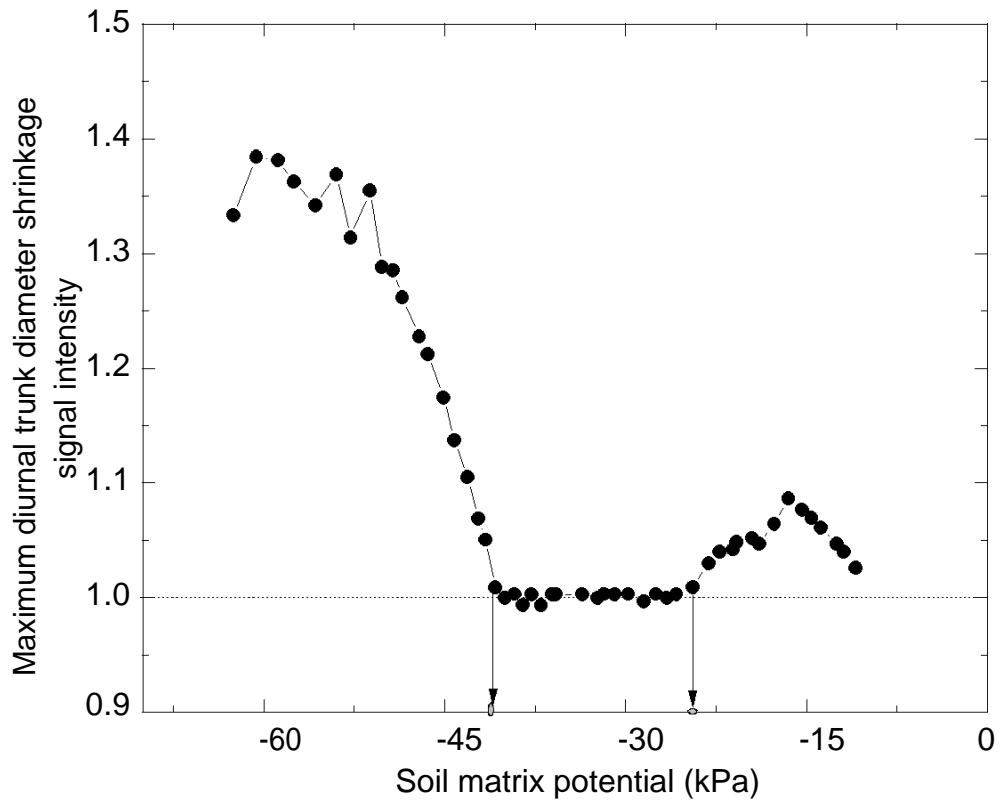
### Definition of suitable soil matrix potential

The dynamic trend of MDS with soil matrix potential is shown in Figure 5. When soil matrix potential was above -40 kPa or below -25 kPa, MDS had an increasing trend with great fluctuations each day, while when soil matrix potential was between -40 kPa and -25 kPa, MDS maintained stable values, with small fluctuations each day.

When MDS intensity was 1.0, it indicated that plants were not subject to water stress associated with irrigation need (Goldhamer and Fereres, 2004). So, a suitable soil matrix potential of pear jujube could be indicated by the measurement of whether MDS signal intensity was 1.0 or not. Data in Figure 6 shows that the suitable soil matrix potential values were in the range of -40kPa to -25kPa



**Figure 5.** Variation of maximum diurnal trunk diameter shrinkage with soil matrix water potential during the measurement period. Each point is the mean of three values.



**Figure 6.** Changes of maximum diurnal trunk diameter shrinkage signal intensity with soil water potential during the experiment. Horizontal line indicates maximum diurnal trunk diameter shrinkage signal intensity value of 1.

according to the MDS intensity signal criteria.

## DISCUSSION

### Soil matrix potential

According to Ruiz-Sánchez et al. (1996), plant water relations under flooding conditions are characterized by a substantial decrease in leaf conductance and leaf water potential as a consequence of anaerobic conditions (of the effects of chemical signals from roots) and an increase in the resistance to water flow through the plant. In T0 plants, leaf conductance and midday leaf water potential remained stable, with merely some slight fluctuations as the season progressed, which indicated that high-frequency irrigation guaranteed a good soil water regime, at the same time, with no water logging occurrence in T0 plants. In T1 plants, before day 165, gas conductance and midday leaf water potential showed a decreasing trend, consistent with results of Ruiz-Sánchez et al. (1996) and this indicated that higher soil matrix potential could be attributed to water logging induced at that time. Between day 165 and 186, gas conductance and midday leaf water potential were the same as values for T0 plants, confirming that the soil matrix potential was not different from that in T0 plants. On day 186 onwards, MDS increased while MXTD, gas conductance and midday leaf water potential decreased which might have been induced by water deficit stress. However, midday leaf water potential decreased at a rate of around  $0.016 \text{ MPa d}^{-1}$  and this shows that soil water deficit stress developed slowly.

### Suitable plant-based indicators

When soil matrix potential changed, MDS, MXTD, gas conductance and midday leaf water potential all responded accordingly. However, the proposals of Naor and Cohen, (2003) should be taken into account when comparing the sensitivity of different plant-based indicators for detecting water stress and the strength of an indicator signal must be seen in the context of its variability (Goldhamer and Fereres, 2001). In this experiment, trunks grew slowly, confirmed by the MXTD mean growth rate of  $0.01 \text{ mm d}^{-1}$ . Zhang et al. (2005) studied the dynamic trend of cotton trunk diameter in different growth stages under water stress conditions and found that MDS was a suitable indicator for the diagnosis of water status because of its sensitivity to water deficit in stopped or slow trunk growth stages, while in the rapid trunk growth stage, faster growth rates concealed the differences of trunk diameter changes caused by short term water deficits and MDS was not a suitable indicator for the diagnosis of water status. Fernández and Cuevas (2010) also proved the same points as Zhang et al. (2005) and confirmed that trunk

diameter fluctuation outputs were affected by seasonal growth patterns, crop load, plant age, size and other factors, apart from water stress. Thus, expert interpretation of trunk diameter fluctuation records is required before using them for scheduling irrigation, which limits their potential for automating the calculation of the irrigation dose. In addition, Remorini and Massai, (2003) also showed that trunk diameter fluctuation and stem flow revealed significant differences between irrigation treatments even in the absence of differences in stem water potential. Ortuño et al. (2007) also indicated that MDS was the most sensitive indicator compared to gas conductance, midday leaf water potential and stem flow.

Plant water status is affected not only by soil moisture but also by meteorological factors. Especially, in arid and semi-arid areas, where irrigation conditions are weaker, climate factors can cause crop water deficit directly or indirectly (Zhang et al., 2008). If the indicator is not sensitive to climate drought, it cannot diagnose crop water status precisely and timely. In this work, MDS and  $ET_0$  as well as  $VPD_{md}$  were positively correlated. So, MDS could also identify the effect of climate on pear jujube water status.

### Influencing factors in defining a suitable soil matrix potential

Anthesis and fruit setting periods are critical times in identifying water requirements of pear jujube (Li et al., 1997). Water stress occurrence in these periods cannot only lead to a large number of buds withering and falling, but also the pollination process is affected (Rodríguez et al., 2007). Young fruit can also be dropped (Cui et al., 2009), which is called early fruit senescence. Irrigation management using soil matrix potential sensors is based on the definition of suitable soil matrix potential threshold values when irrigation is required or stops. In the study, the soil matrix potential upper and lower threshold values were found to be  $-25 \text{ kPa}$  and  $-40 \text{ kPa}$ , respectively. This is compatible with but improves on published studies showing that suitable soil matrix potential values lie between  $-150 \text{ kPa}$  and  $-20 \text{ kPa}$  (Taylor, 1965; Bower et al., 1975; Wang et al., 2005). Differences between soil matrix potential threshold values of this and other studies can be attributed to site-specific factors (González, 2003), the evaporative demand of experiments (Thompon et al., 2007) and the higher sensitivity of maximum diurnal trunk diameter shrinkage compared to agronomic differences, to detect differences, as well as specific plant species.

In irrigation management, wilting coefficient is also a very important parameter. Generally, the soil matrix potential is considered as  $-1500 \text{ kPa}$ , when wilting in plant happens. Under the soil matrix potential value, in some crops that require high moisture, permanent wilting or death may happen, while forest trees, especially the tree species with the characteristic of drought resistance,



may not die such as pear jujube trees; they can re-sprout after restoration of water and even when subjected to severely water deficit stress resulting to all leaves falling off. The definition of dead soil matrix potential is complex and further studies need to be done.

## Conclusions

When soil matrix potential rose or fell, MDS, MXTD, gas conductance and midday leaf water potential all responded accordingly. With increase in MDS, MXTD growth rate, gas conductance and midday leaf water potential all decreased to different degrees. However, MDS could respond on the same day that the soil matrix potential changed, while, the other indicators responded two or three days later. With smaller noise and the biggest signal intensity, the MDS signal intensity to noise ratio was highest in 15 days of higher soil matrix potential values and 19 days of lower soil matrix potential. MDS changes also showed close relationships with meteorological factors, with correlations between MDS and  $ET_0$  or  $VPD_{md}$  of 0.702 or 0.605, respectively. Thus, MDS could comprehensively reflect the effect of soil moisture and climate on crop water status and be used as a suitable indicator for precise irrigation of pear jujube in anthesis and fruit setting periods. When soil matrix potential was below -40 kPa or above -25 kPa, MDS increased and MDS signal intensity was above 1, indicating that pear jujube was subjected to water stress at the research site. Accordingly, the suitable soil matrix potential of pear jujube in anthesis and fruit setting periods was between -40 kPa and -25 kPa.

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