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Full Length Research Paper

Improved irrigation scheduling for pear-jujube trees based on trunk diameter sensing data

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A suitable indicator for scheduling pear-jujube (*Ziziphus jujuba* Mill.) irrigation in China was developed based on trunk diameter fluctuations (TDF). Parameters derived from TDF responses to variations in soil matrix potential (Ψ_{soil}) were compared under deficit and well irrigation. Maximum daily shrinkage (MDS) increased with higher Ψ_{soil}, whereas daily maximum trunk diameter and daily growth decreased with lower Ψ_{soil}. MDS signal intensity (actual MDS/reference MDS) to noise ratio was highest in response to higher and lower Ψ_{soil}. The advantage of MDS in automatic irrigation scheduling compared with other TDF-derived parameters was its prompt reliable response to water deficit, with less effect of phenophase. Based on the MDS signal threshold values, the Ψ_{soil} without irrigation-related stress was in the range of -40 to -25 kPa during anthesis and setting, and -53 to -35 kPa during fruit development. The MDS signal was around 1.30 when the Ψ_{soil} ranged from -80 to -67 kPa during fruit development, indicating drought stress. In addition, leaf water use efficiency increased under these conditions, but photosynthetic rate and transpiration rate decreased. Vegetative growth was reduced, but individual fruit weight increased and compensated for yield losses caused by water deficit. These values can facilitate precise irrigation and deficit irrigation of pear-jujube in China.

Key words: Drought stress, trunk diameter fluctuations, soil matrix potential, jujube (*Ziziphus jujuba* Mill.), anthesis and fruit-setting periods, fruit development period.

INTRODUCTION

Pear-jujube is widely cultivated in the Loess Plateau region of China where it has been adopted by a project aimed at returning farmland to forest. Pear-jujube culture was previously constrained by the wasteful use of limited water supplies that characterize traditional irrigation, which restricted the development of local agriculture. It is important to balance the needs of the project directed toward returning farmland to forest and the needs of the rural economic structure, which will jointly advance the ecological environment and improve rural economic development in Northwest China (Tian and Liu, 2004).

As a consequence, there is a need to develop new irrigation scheduling techniques that optimize water use. In this respect, the use of plant indicators may be the ideal method for irrigation scheduling because they exploit the dynamic nature of plant water status and they are the link to crop productivity (Remorini and Massai, 2003; Jones, 2004; Liu et al., 2009). Trunk diameter fluctuations (TDF) (Huguet et al., 1992; Cabibel et al., 1997; Cohen et al., 2001; Ortuño et al., 2004), leaf water potential (Peretz et al., 1984), and predawn leaf water potential (Améglio et al., 1999) are all regarded as appropriate indicators for diagnosing plant water status. However, measuring the actual water potential requires frequent field visits and significant manpower because

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Table 1. Soil matrix potential with different treatment in different years.

Year	Treatment	Soil matrix potential (kPa)	Field moisture capacity (%)
2009	T_0	–33 ~ –25	84 ~ 90
	T_1	–10 ~ –68 ~ –25	120 ~ 60 ~90
2010	T_0	–51 ~ –41	75 ~ 80
	T_1	–84 ~ –68	60 ~ 65

frequent manual readings are required if measurement cannot be automated (Ortuño et al., 2004)

In contrast, TDF measurement provides a continuous and automated record of plant water status, permitting a reduction in the manpower needed for commercial orchard management. Furthermore, TDF measurement does not harm the plant (Kozlowski and Winget, 1964). Although TDF derived indices show a high plant-to-plant variability, in most cases, the signal intensity is high enough to achieve an acceptable sensitivity (Fernández and Cuevas, 2010; Ortuño et al., 2010). Daily maximum (MXTD) and minimum (MNTD) trunk diameter, maximum daily shrinkage (MDS), daily growth (DG) and recovery time can all be derived from TDF on a daily basis.

Many researchers have suggested that MDS (Goldhamer and Fereres, 2004; Ortuno et al., 2009; Meng et al., 2004, 2006) is an appropriate indicator for the diagnosis of plant water status. However, Goldhamer and Fereres (2001) suggested MXTD offers a more consistent indicator for scheduling irrigation than MDS for rapidly growing young peach trees. It was also reported that a DG value of zero is probably the best irrigation threshold for adult peach trees (Zhan et al., 2009). To the best of our knowledge, there are fewer previous studies of pear-jujube water content prediction based on TDF, although Zhang et al. (2010) studied pear-jujube irrigation scheduling and proposed the MDS as an appropriate indicator. Nevertheless, the irrigation scheduling for pear-jujube need more further studies based on TDF.

The aim of this study was to determine the most appropriate indicator for the diagnosis of pear-jujube water needs by comparing the sensitivity and stability of parameters derived from TDF in response to Ψ_{soil} changes, including MDS, MXTD and DG. We intended to define a suitable Ψ_{soil} for pear-jujube during the anthesis and fruit-setting periods, and the fruit development period based on the relationship between an appropriate indicator and Ψ_{soil}. The effects of deficit irrigation on pear-jujube trees were also discussed.

MATERIALS AND METHODS

Site description and experimental design

Experiments were performed in a commercial pear-jujube (*Ziziphus jujuba* Mill, grafted on wild jujube, *Z. jujuba* Mill. var. spinosa (Bunge) Hu ex H. F. Chow) orchard in Mengcha, Mizhi, Shanxi, China (38.18° N, 109.47° E). The experiment was conducted over two consecutive seasons (2009 to 2010), which corresponded to the third and fourth year since the trees were planted. At the beginning of the experiment, the average trunk diameter, height and canopy diameter of the trees were 2.39, 68.44 and 25.94 cm, respectively. The site was a hilly ravine area of the Loess Plateau in a semi-arid zone with a mean annual precipitation of 393 mm, which is mainly concentrated in the period between July and September. The soil type was loess with a uniform texture and moderate permeability. The mean bulk density was 1.29 g cm^{-3} in the upper 1.0 m of the soil profile. Field moisture capacity (FMC) was an average of 23% in the upper 1.0 m of the soil profile (mass percentage) (Zhang et al., 2010).

Irrigation treatments were applied during the pear-jujube anthesis and fruit-setting periods in 2009, and during the fruit development period in 2010. Two levels of water treatments (T_0 and T_1) were applied to pear-jujube trees to determine their water requirement during different phenological periods. In 2009, the control plants (T_0) were well irrigated and maintained with a Ψ_{soil} between -33 and -25 kPa during the anthesis and fruit-setting periods. T_1 plants were initially irrigated to produce a Ψ_{soil} corresponding to 120% FMC, after which irrigation was withdrawn and the Ψ_{soil} dropped naturally. When the Ψ_{soil} dropped below -68 kPa (60% FMC), water was applied to match the T_0 treatment. In 2010, control plants (T_0) were well irrigated and maintained with an Ψ_{soil} between -51 and -41 kPa during the fruit development period, while T_1 plants were maintained with an Ψ_{soil} between -84 to -68 kPa (Table 1). Each treatment occupied one plot measuring 6 × 1 × 1 m (length × width × depth) situated under a mobile rain shelter that protected them from rainfall. The two plots were adjacent and a row of three trees was planted in each plot and two trees were labeled for repetitions in time.The study site was equipped for drip irrigation. Two pipes were provided to ensure uniformity of irrigation and each had four drippers evenly installed in each pipe, where each emitter discharged at a rate of 4 L h^{-1}. Irrigation timing was controlled automatically by a water potential-controlled irrigation system. When the Ψ_{soil} dropped below the lower limit, information was sent to an electromagnetic valve that activated automatic irrigation for 5 min. If the Ψ_{soil} was still lower than the set value after 30 min, this process was repeated until the Ψ_{soil} was greater than the upper limit.

Soil matrix potential measurement

Soil matrix potential was measured using an equilibrium tensiometer (model EQ15 basic, range –1500 to 0 kPa, accuracy ± 10 kPa, Ecomatik, Germany). Each plot had three soil matrix potential sensors at a depth of 30 cm. Two were buried between the trees and linked to a data logger (model DL2e, Delta-T Devices, U.K.), while the other was located 15 cm from the middle tree and

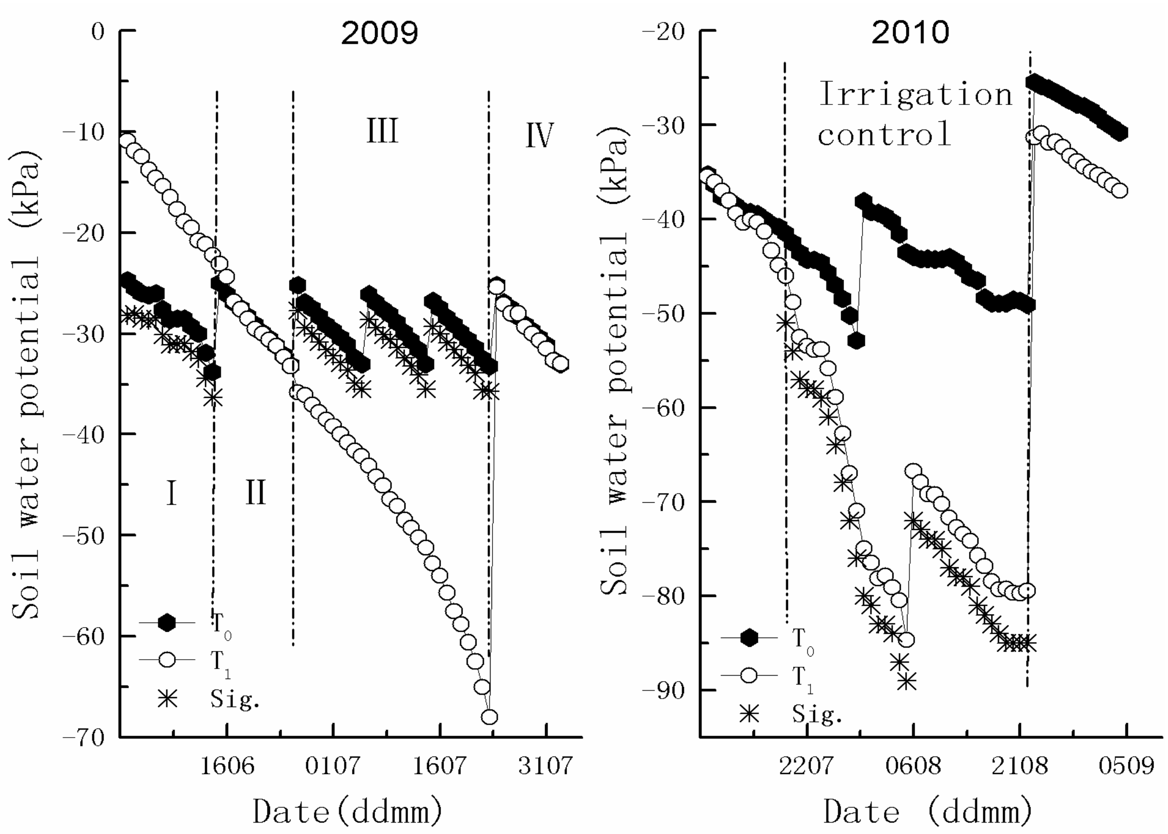

Figure 1. Dynamic trends of soil matrix potential for different treatments in 2009 and 2010. Means followed by asterisk (*) indicate significant differences at $p < 0.05$ between two treatments. Each point is the mean of triple values. For the date, ddmm indicate the day and month.

connected to another data logger (model GP1, Delta-T Devices, U.K.) that controlled automatic irrigation. Measurements were taken every 10 s and the data loggers were programmed to report 30 min means.

Trunk diameter fluctuations measurement

Trunk diameter fluctuations were measured throughout the experimental period for each tree using linear variable displacement transducers (LVDT) (model DF, range 0 to 11 mm, accuracy ± 7 µM, Ecomatik, Germany) attached to the trunk using a special bracket made of invar and aluminum. Sensors were placed on the north side and covered with silver thermo protective foil to prevent wind, temperature and rain from affecting the devices. All the sensors were linked to a data logger (model DL2e, Delta-T Devices, U.K.). Measurements were taken every 10 s and the data logger was programmed to report 30 min means.

Eco-physiological indicators

Photosynthetic data was measured using a portable photosynthesis system (LI-6400xp, LI-COR Bioscience, USA) on sunny days (14th to 16th August in 2010) from 9:00 to 19:00. Three trees were measured in each treatment every two hours. The number of fruit-bearing branchlets and fruit was counted manually. Single fruit weight was measured using a balance after the harvest.

Statistical analysis

Tree size data were the mean values for triplicate trees, while photosynthetic data were the mean values of three days. All measured variable were first characterized using descriptive statistics with SPSS 16.0 (SPSS Institute, USA). The coefficients of variation were calculated from these statistics. Significant effects of all variables between treatments were tested using a one-way ANOVA on SPSS16.0. The graphs were created by Origin 8.0 (Origin Lab, USA).

RESULTS

Dynamic changes in soil matrix potential

Irrigation was applied six times during the experiment in the 2009 T_0 treatment, in which Ψ_{soil} was almost stable in the range of -25 to -33 kPa (Figure 1). However, the Ψ_{soil} showed a different response with the T_1 treatment. This treatment was irrigated to -10 kPa initially, but it then showed a marked tendency to decrease and dropped to a minimum value of -68.3 kPa. The T_1 treatment was irrigated to -25 kPa immediately the value dropped below -68 kPa (60% FMC). Soil matrix potential exhibited four discrete stages in the T_1 treatment when compared with as follows: water logging (I); no different stage (II); irrigation control (III) and post- irrigation (IV), which exhibited no difference from the T_0 treatment.

In 2010, the Ψ_{soil} was -35 kPa at the beginning of the experiment with both treatments. The Ψ_{soil} declined naturally and reached a predetermined range with the passage of time. In the entire experiment, both treatments were irrigated twice. In the T_0 treatment, trees were irrigated on 30th July and on 24th August, respectively, and then on the 6th and 24th of August in the T_1 treatment. The first scheduled irrigation point was determined when the Ψ_{soil} reached the lower limit, while the second irrigation point conformed to the end of the fruit development period. The Ψ_{soil} appeared significantly different between treatments from 19th July to 24th August in 2010 ($p < 0.05$), which was referred to as the irrigation control.

Trunk diameter fluctuations

The MDS, MXTD and DG during the two seasons (2009 to 2010) are shown in Figure 2. In T_0 plants, the MXTD increased continuously during the experimental period, with a mean growth rate of 0.034 mm day^{-1} in 2009 and 0.112 mm day^{-1} in 2010 (Figures 2A and D), which probably reflected the different phenological periods (Zhan et al., 2009). In 2009, the MXTD values for T_1 treatment dropped gradually as a result of a higher Ψ_{soil} and the decrease was significant between treatments of 3rd and 16th June ($p < 0.05$). Subsequently, the Ψ_{soil} declined, but MXTD was not significantly different between treatments between 17th June and 6th July ($p > 0.05$). During the water deficit period, the daily MXTD growth rate dropped again and was significantly different ($p < 0.05$) between treatments from 7th July (six days after irrigation control) to 29th July (seven days after irrigation). In 2010, significant differences were detected on 30th July (11 days after the irrigation control) and the difference between treatments ($p < 0.05$) continued until the end of the experiment.

In the T_0 treatment, the MDS fluctuated throughout the whole experimental period (Figures 2B and E). Differences between treatments were significant between 2nd and 15th June in 2009 ($p < 0.05$), which resulted from an increase of MDS in the T_1 treatment under the higher Ψ_{soil} condition. The Ψ_{soil} in T_1 treatment was closer to T_0 treatment, while the MDS in T_1 treatment kept similar values to T_0 treatment between 16th June and 3rd July in 2009. From 4th to 25th July in 2009, the differences between treatments were significant ($p < 0.05$) due to the increased MDS in the T_1 treatment under lower Ψ_{soil} conditions. Furthermore, from 26 July onward, there was no significant difference ($p > 0.05$) between treatments. The same trend also occurred in 2010. When Ψ_{soil} of the two treatments were similar, there was no difference between MDS of treatments in the ranges from 8th to 18th July and from 23rd August to 4th September in 2010. And MDS values in T_1 treatment were greater than T_0 treatment significantly when Ψ_{soil} in T_1 treatment was lower than T_0 treatment between 25th July and 25th August in 2010.

The DG fluctuated and followed an increasing trend in the 2009 experiment period, whereas the DG increased initially in 2010 and then decreased with time. This could be attributed to different phenological periods (Zhan et al., 2009). When Ψ_{soil} of theT_1 treatment was not significantly different from T_0, there was no significant difference between the DG in the two treatments ($p > 0.05$). The DG dropped in the T_1 treatment due to deficit irrigation between 3rd and 29th July in 2009. After irrigation, the difference disappeared immediately. However, the difference ($p < 0.05$) was most apparent between 27th July and 22nd August in 2010, during the period of deficit irrigation. On other days, the DG occasionally behaved significantly different between the two treatments.

Responses of trunk diameter fluctuations to changes in soil matrix potential

We measured the midday leaf water potential in 2009 experiment. The values in T_0 treatment were high and fairly constant during the experimental period, and reached value of -1.98 MPa (Zhang et al., 2010). This trend of midday leaf water potential in T_0 treatment was similar to the treatment of non- limiting soil water conditions as reported by Ortuño et al. (2005). In 2010, although midday leaf water potential was not measured, the soil water potential was based on results of 2009 experiment. That is to say, T_0 treatment was not under drought stress in 2009 and 2010.

In order to eliminate the effect of meteorological factors on TDF, we calculated the signal intensity using the T_1 value/T_0 value, or the T_0 value/T_1 value. The signal intensities of the three parameters in consecutive seasons are shown in Figure 3. The different degrees of response are shown with higher/lower Ψ_{soil}. The MDS and DG responded more rapidly than MXTD in the two seasons. The signal intensities of the three parameters all remained at a value of 1.0 for different periods, when the Ψ_{soil} in the T_1 treatment was similar to that in the T_0 treatment. Water logging and water deficit led to increases in the MDS, MXTD and DG signal intensity and these values began to rise significantly above a value of 1.0 at different times.

In 2009, the MDS, MXTD and DG signal intensities

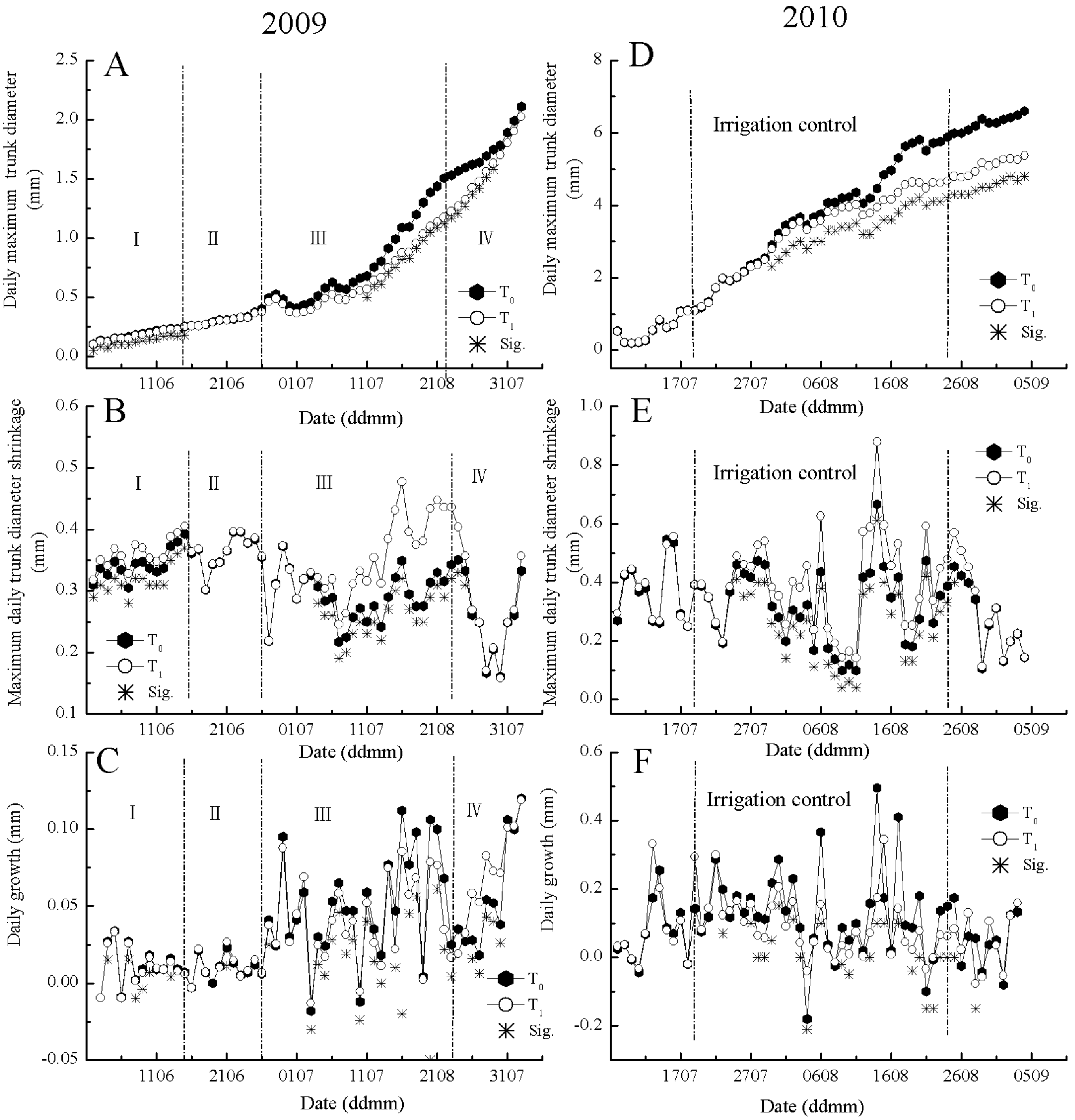

Figure 2. Dynamic trends of maximum daily shrinkage, maximum daily trunk diameter and daily growth for different treatments in 2009 and 2010. Means followed asterisk (*) indicate significant differences at $p < 0.05$ between two treatments. Each point is the mean of triple values. For the date, ddmm indicate the day and month.

dropped to a value of 1.0 two days, six days, and one day after irrigation, respectively. In 2010, only the MDS and DG dropped to a value of 1.0 on the third day after irrigation. The MXTD signal intensity remained at 1.23 until the end of the experiment, which compensated for the decrease in DG during the late period of August. The MDS and MXTD signal intensities changed slightly, whereas the DG signal intensity fluctuated greatly.

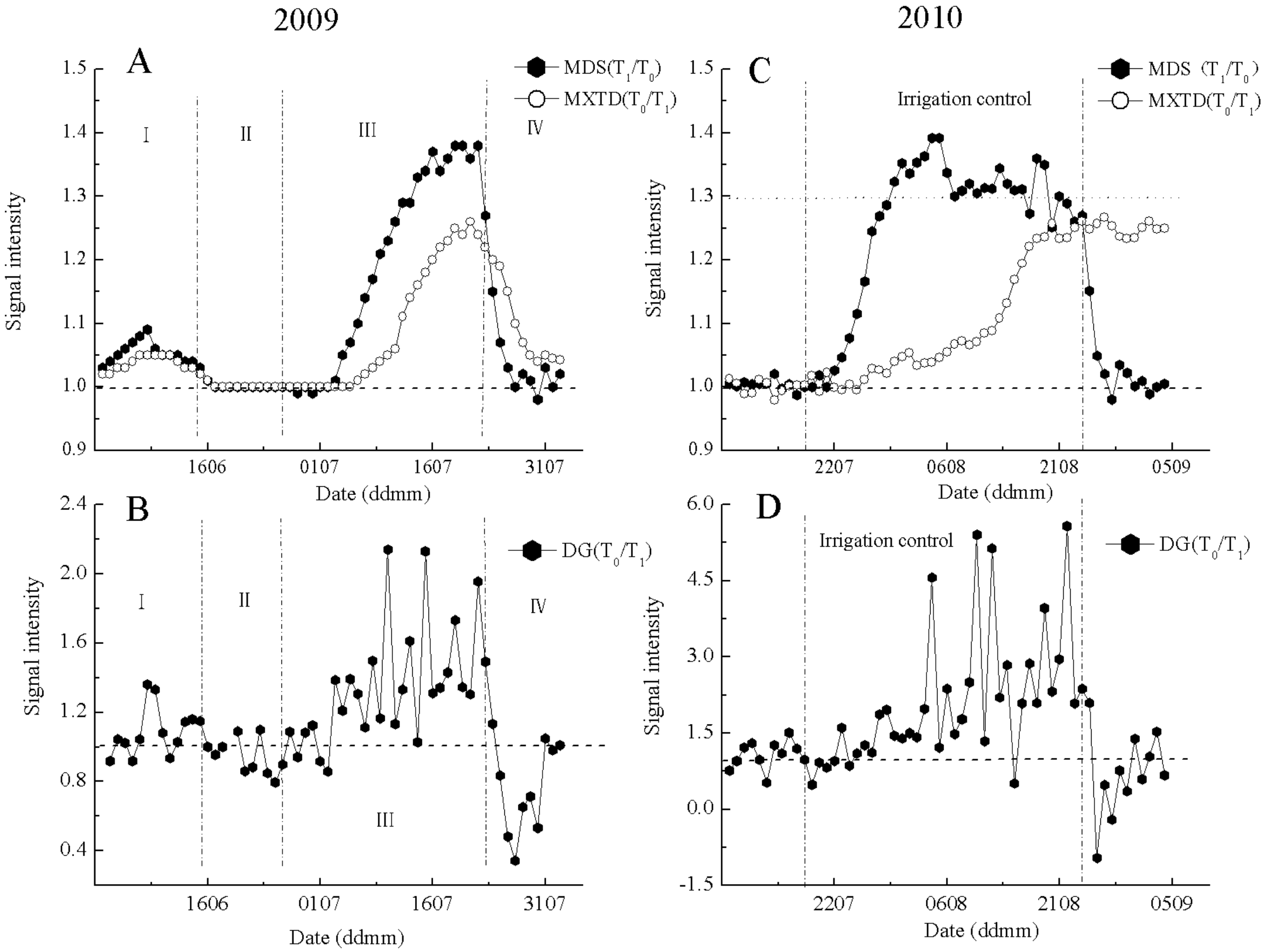

Figure 3. Dynamic trends of signal intensities of maximum daily shrinkage, maximum daily trunk diameter and daily growth in 2009 and 2010. Horizontal line indicates maximum daily shrinkage signal intensity value of 1. And in part C, horizontal line indicated maximum daily shrinkage signal intensity value of 1.3. For the date, ddmm indicate the day and month.

Significant differences in DG were occasionally observed between different treatments (p<0.05).

Given the changes in plant water status during the short period of time when the soil moisture changed (Ortuño et al., 2005), the signal intensity and noise (coefficient of variation) were analyzed for all indicators during irrigation control in 2009 between 3rd and 23rd July, and in 2010 between 25th July and 23rd August.

The data in Table 2 shows that the mean signal intensity of DG was higher than that of MDS and MXTD in 2009 and 2010. The mean noise of MDS was lower than both DG and MTXD in 2009 and 2010. The signal intensity to noise ratio of MDS was the highest, indicating that MDS was more sensitive than the other two indicators derived from TDF when diagnosing pear-jujube water status in our experimental conditions.

Definition of suitable soil matrix potential

When the MDS signal intensity was 1.0, it indicated that plants were not subjected to drought stress associated with irrigation need (Goldhamer and Fereres, 2004). Thus, a suitable Ψ_{soil} for pear-jujube could be indicated by measuring whether the MDS signal intensity differed from 1.0. The data in Figure 4 indicates that suitable Ψ_{soil} values for pear-jujube during anthesis and fruit-setting periods were in the range of -40 to -25 kPa (Zhang et al., 2010). The 2010 data indicated that a suitable Ψ_{soil} value for pear-jujube during the fruit development period was in the range of -53 to -35 kPa, which agrees with the fact that the T_0 treatment was well-irrigated at this time. When the Ψ_{soil} ranged from -67 to -80 kPa, the MDS signal intensity varied around 1.30 (Figure 4), which indicated

Table 2. Responses of maximum daily shrinkage, maximum daily trunk diameter and daily growth to water deficit stress.

Diagnostic indicator	$3^{rd} - 23^{rd}$ July in 2009			25th July – 23rd August in 2010		
	Signal intensity	Noise	The ratio of signal intensity to noise	Signal intensity	Noise	The ratio of signal intensity to noise
MDS	1.25^a	0.053^a	23.80	1.31^a	0.065^a	20.15
MXTD	1.12^b	0.065^b	17.20	1.09^b	0.095^b	11.47
DG	1.44^c	0.143^c	10.07	2.20^c	0.158^c	13.92

MDS is maximum diurnal trunk diameter shrinkage; MXTD is daily maximum diameter; DG is daily growth. Different letters within a column indicate significant differences at $p < 0.05$.

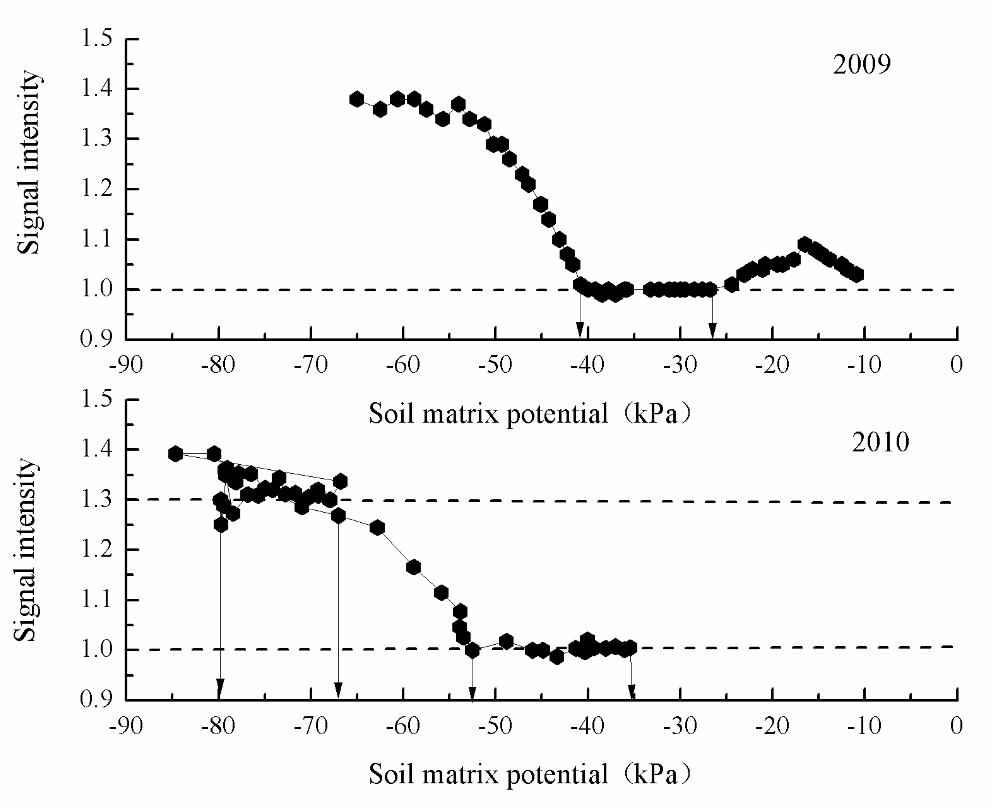

Figure 4. Changes of maximum daily shrinkage signal intensity with soil matrix potential in 2009 and 2010. Horizontal line indicates maximum daily shrinkage signal intensity value of 1. Under 2010, horizontal line indicated maximum daily shrinkage signal intensity value of 1.3.

that the trees in T_1 treatment were under deficit irrigation.

The influence of deficit irrigation on photosynthetic production

The diurnal variation curve of the net photosynthetic rate (P_n) had one peak value and the P_n in the T_1 treatment was lower in well-irrigation (Figure 5). The maximum P_n with well-irrigation appeared at 13:00 h, whereas with T_1 treatment the P_n peak appeared at 15:00 h. This may be because the stomata were closed at high noon tominimize transpiration. The same curve was observed for the transpiration rate (T_r), but the maximum for both treatments appeared at 15:00h (Figure 5B).

This resulted in higher leaf water use efficiency (WUE) with the T_1 treatment before 17:00 h, but the trend changed at 19:00 h when the leaf WUE of T_1 treatment dropped below that of T_0 treatment. This may be attributed to closed stomata and the decrease in the P_n of the T_1 treatment at 19:00 h. Based on these data, we can conclude that mild irrigation control can improve leaf

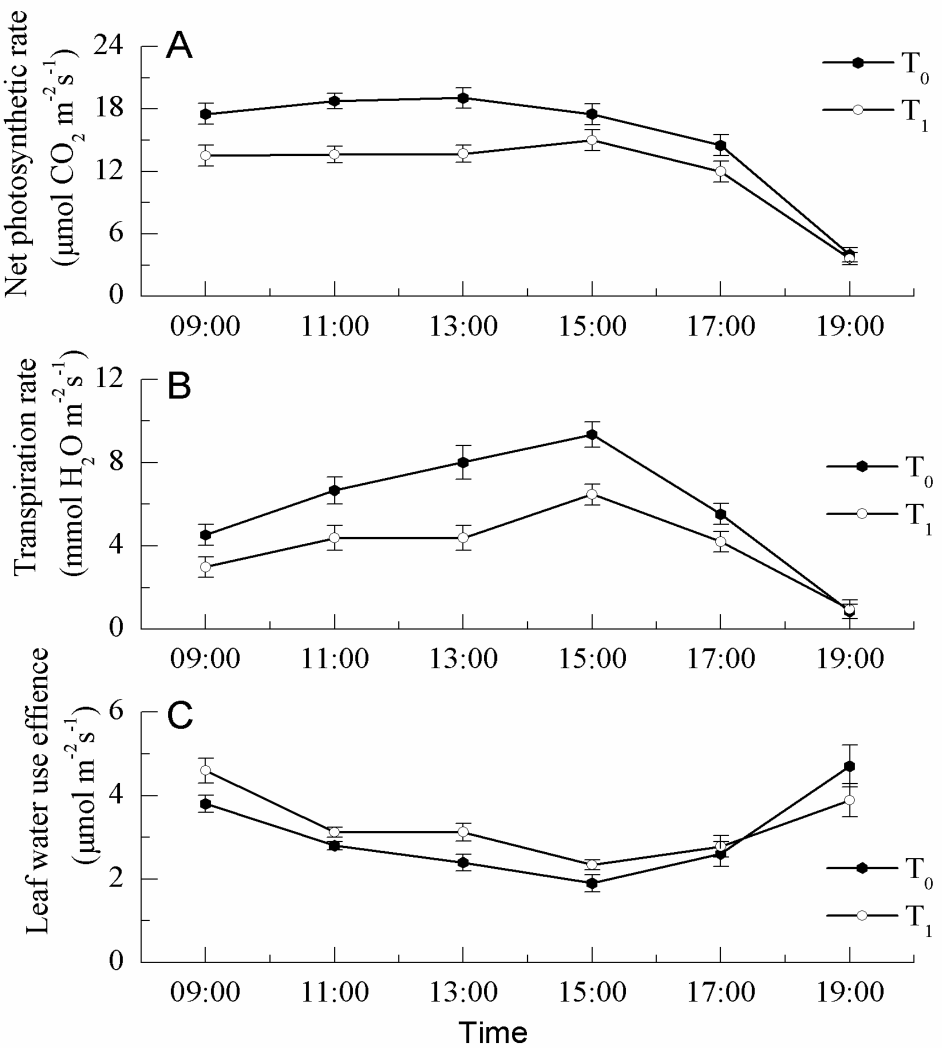

Figure 5. Index of photosynthesis parameter under different water treatments in August 2010. Each point is the mean of three days.

WUE.

T_0 treatment trees produced 74 fruit-bearing branchlets during the study period, whereas T_1 treatment trees produced only 37 fruit-bearing branchlets. The stem diameter growth with the T_0 treatment was significantly greater than that with the T_1 treatment ($p<0.05$) (Table 3). However, the single fruit weight with the T_1 treatment was significantly higher than the T_0 treatment ($p<0.05$), which compensated for the yield losses caused by water deficit.

DISCUSSION

Suitable plant-based indicators

Zhan et al. (2009) suggested that a DG value of zero is probably the best irrigation threshold for peach trees. However, the DG did not exhibit continuous negative values during our study over two seasons, although the T_1 treatment was conducted with drought stress. Therefore, it is not possible to judge the water content of pear-jujube based on a positive or negative value of DG. This could be due to the drought-resistance of pear-jujube (Chen 1991). Furthermore, the signal intensity to noise ratio was lowest for DG and the signal intensity was unstable. Therefore, DG is not a suitable indicator.

The signal intensity of MXTD changed slightly and it is regarded as a consistent indicator when scheduling irrigation for rapidly growing young peach trees (Goldhamer and Fereres 2001). However, it was hard to agree with this viewpoint in our experiment. The trees were three-years old and grew rapidly, but MXTD failed to immediately reflect the pear-jujube water content. A lag time of 14 days was found between differences in the

Table 3. Growth of trees and photosynthetic productivity under different water treatments.

Treatment	Branchlet number	Trunk growth (mm)	Fruit number	Single fruit weight (g)	Production (g)
T_0	74^a	6.61^a	68^a	33.05^a	2412.64^a
T_1	37^b	5.37^b	62^b	42.41^b	2629.42^a

Different letters within a column indicate significant differences at $p < 0.05$.

similar to the T_0 treatment after the experiment, whereas the MXTD in the T_1 treatment was clearly smaller than the T_1 treatment after the experiment in 2010 ($p<0.05$). Thus, MXTD is not a suitable indicator.

In contrast, we found that MDS appeared to be a reliable water stress indicator for pear-jujube trees. During the two-year study, the MDS values of trees with the deficit-irrigated treatment were consistently higher than those in well-irrigated plots, which was similar to reports with other species of fruit trees (Intrigliolo and Castel, 2006; Fereres and Goldhamer, 2003; Naor and Cohen, 2003). The signal intensity of MDS changed only slightly, with a greater signal intensity and lower noise. The ratio of signal intensity to noise was greatest for MDS. MDS reacted quickly at the onset of water stress, which was eight days earlier than MXTD in 2009 and six days earlier than MXTD in 2010. When the Ψ_{soil} ranged from -68 to -80 kPa, the MDS signal intensity varied around 1.30. The other parameters examined in this study did not exhibit this response. MDS may well be a superior tree-based indicator that can be used when regulated deficit irrigation and precise irrigation scheduling are needed (Goldhamer and Fereres, 2004).

Suitable soil matrix potential

The anthesis and fruit setting periods, and the fruit development period are critical times for identifying the water requirements of pear-jujube (Li et al., 1997). Although drought stress during the anthesis and fruit-setting periods can lead to a large number of buds withering and falling, it can also affect the pollination process (Rodriguez et al., 2006). Young fruit may drop because of drought stress during the fruit development period (Cui et al., 2009b) and the single fruit weight is affected. All of these outcomes can therefore influence the yield. In the current study, the pear-jujube trees were not under drought stress when the MDS signal was 1.0. Thus, an appropriate Ψ_{soil} was in the range of -40 to -25 kPa during the anthesis and fruit setting periods, while in the fruit development period the range was from -53 to -35 kPa. These values represented an improvement in accuracy compared with published studies, thus suggesting that suitable Ψ_{soil} values fell in the much wider range of -150 to -20 kPa (Taylor, 1965; Bower et al., 1975). Differences in the Ψ_{soil} threshold values between this and other studies can be attributed to site-specific factors (González, 2003), evaporative demand (Thompson et al., 2007), and the higher sensitivity of the MDS compared with agronomic differences used to detect differences, as well as the specific plant species used in the experiment.

When MDS signal varied around 1.30, the trees were in water stress and the Ψ_{soil} was in the range of -80 to -67 kPa. In these conditions, the leaf WUE increased as the P_n and T_r decreased. Moreover, the P_n decreased, but the photosynthate distributed to fruit was not reduced because this treatment did not result in a significant reduction in production ($p>0.05$), although there was a reduction in vegetative growth (fruit-bearing branchlets and trunk diameter). The fruit-bearing branchlets produced under these conditions were always of short length, with fewer leaves and buds, but no capacity for setting fruit (Chen, 1991).

The intensity of water stress optimized the balance between reproductive and vegetative growth, which agrees with Cui et al. (2009a). This treatment also increased the single fruit weight, which compensated for the loss caused by a lower number of fruit. However, KIlili (1996) discovered that deficit irrigation reduced the single fruit weight. This may be due to the different soil water content and different species. The flowering period of pear-jujube tree is long (sometimes 50 days) and if soil water was sufficient, then the time of setting fruit would be postponed to fruit development period (Chen 1991). However, the fruit of jujube set in fruit development period had reduced growth time than those set in fruit setting period, which results in fruits being small and light. Hence, T_0 treatment had no water limitation and had fruit set in fruit development period, which resulted in light single fruit weight.

Conclusion

Based on our study, there are two methods for controlling precise irrigation or deficit irrigation. First, we can use the MDS signal based on reference trees. Secondly, we determined a suitable Ψ_{soil} threshold value using the MDS signal intensity. Irrigation can be controlled automatically using a GP1 (Delta-T Devices, U.K.).

This method still requires the determination of threshold values that are non-limiting and mild-limiting for jujube tree growth. However, determination of the threshold MDS signal and Ψ_{soil} still requires much work because the effects of deficit irrigation on a tree's growth in the next season and throughout a tree's life remain unknown.

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