# Responses of young 'Pink lady' apple to alternate deficit irrigation following long-term drought: growth, photosynthetic capacity, water-use efficiency, and sap flow

X.P. SUN, H.L. YAN, P. MA, B.H. LIU, Y.J. ZOU, D. LIANG, F.W. MA[+], and P.M. LI

*State Key Laboratory of Crop Stress Biology in Arid Areas, College of Horticulture, Northwest A&F University, Yangling, Shaanxi – 712100, China*

## Abstract

We studied photosynthetic capacity, growth, sap flow, and water-use efficiency in young trees of 'Pink Lady' apple (*Malus domestica*) that were exposed to 60 d of moisture stress. Three irrigation schemes were tested in the greenhouse: well-watered control; drought; or alternate deficit irrigation (ADI). Compared with the drought-stressed plants, those treated *via* ADI showed better height growth, larger scion diameters, and greater total leaf area, as well as significantly increased gains in dry biomass and rootstock diameters. However, their performance was still significantly lower than that demonstrated by continuously well-watered plants. Sap flow was greater under ADI than under drought, but less than under control conditions. The average rate of net photosynthesis, total amount of irrigation water applied, and dry biomass gain had highly significant and positive linear correlations with long-term water-use efficiency ($WUE_L$). The same was true between average stomatal conductance and $WUE_L$. By contrast, instantaneous water-use efficiency ($WUE_I$) was very significantly and negatively correlated with $WUE_L$. In addition, values for $WUE_L$ were much higher from well-watered plants when compared with either drought-stressed trees or those treated per ADI. Therefore, our results indicate that, although 'Pink Lady' apple normally has high WUE, it still consumes a large amount of water. Therefore, the practice of ADI following a period of long-term drought could be used to improve growth and $WUE_L$ by this cultivar.

*Additional key words*: apple; deficit irrigation; photosynthetic capacity; sap flow; water-use efficiency.

## Introduction

Water stress is an important environmental factor that can limit plant performance during the initial phases of growth and establishment (Yin *et al.* 2005). Such a deficiency can affect stomatal conductance, net photosynthesis, and water-use efficiency (WUE) (Chaves *et al.* 2010, Egilla *et al.* 2005, Massonnet *et al.* 2007).

In drought-prone regions of the world, improvements to WUE can be accomplished through methods that include water-saving irrigation (Chaves *et al.* 2007, Cui *et al.* 2008). Theoretically, roots functioning under dry conditions can promote hydraulic and chemical signals, thus reducing their stomatal conductance, transpiration rate, and shoot growth while enhancing WUE (Bindon *et al.* 2008, Chaves *et al.* 2010). For example, Sadras (2009) and García *et al.* (2012) have shown that Partial Root-Zone Drying Irrigation is economically justified; moreover, substantial gains in WUE can be achieved by closely monitoring the amount of water applied under deficit conditions. However, Elias and Auxiliadora (2007) have suggested that such deficit irrigation may in fact diminish WUE. Plant water status is mainly determined by a genotype. Various defense or tolerance mechanisms can be utilized under drought, and sap flow can serve as an indicator for detecting plant responses during periods of water stress (Chirino *et al.* 2011, Ortuño *et al.* 2006).

Apple is one of the most economically important fruits worldwide; its production and consumption are highest in China. There, apple trees are often cultivated in arid and semiarid regions where they are susceptible to drought. Therefore, irrigation is a vital tool for effective horticultural production. Here, we characterized the photosynthetic capacity, biomass allocation, sap flow, and WUE of 'Pink Lady' apple when young trees were exposed in the greenhouse to different irrigation treatments: (*1*) well-watered control, (*2*) moderate drought, or (*3*) alternate deficit irrigation (ADI) after long-term water stress. Our objectives were to analyze the relationships among WUE and various growth parameters, and to investigate whether the use of ADI after long-term drought could improve performance by 'Pink Lady' apple.

## Materials and methods

**Material and experimental design:** Experiments were conducted at Northwest A&F University, Yangling, China (34° 20'N, 108°24'E) between March and August of 2010. We used one-year-old scions of 'Pink Lady' apple (*Malus domestica*) grafted onto two-year-old *M. hupehensis* (Pamp.) Rehd. rootstock. In late March, all plants were placed in plastic pots (28 × 21 cm) that were filled with sand, cow dung, and clay soil (1:1:1, v:v:v). The soil mixture pH was 7.52 ± 0.31. All pots initially weighed the same (9.5 kg) to facilitate calculations and maintenance of a specific field capacity (FC) *via* the weighing method. FC was determined by first saturating the pots with water, then allowing the gravimetric water to drain for 24 h before the pots were weighed. The water content was calculated as FC by the following equation:

$$FC = (SM - DM)/DM$$

where SM was the mass of the pot when the soil was saturated, and DM was the pot dry mass. After applying standard irrigation (to 70% FC) for 60 d in the greenhouse, we selected uniform, healthy plants and separated them into two groups: (*1*) well-watered control trees that were maintained at 70% FC (total pot mass 10.2 kg), and (*2*) drought-stressed plants, from which irrigation was withheld for approximately 1 d until the total pot weight decreased to 9.6 kg (55% FC). To minimize surface evaporation, a 5-cm-thick layer of sand was spread on the soil surface of each pot. For the second treatment group, the soil water content was maintained at a constant level for 60 d by "adding-back" the amount of water that would compensate for that lost *via* evapotranspiration. Afterward, half of those drought-stressed plants were then exposed to the practice of alternate deficit irrigation (ADI) for 30 d. This involved increasing the FC to 70% for the first 10 d, then reducing it to 55% for another 10 d before raising it again to 70% for the final 10 d of the experimental period. Evapotranspiration water loss was defined as the average decrease in mass per pot (*n* = 5), as determined with a balance (15.0-kg capacity, 0.5-g resolution; *SÉMUP, Model ACS-15*, China). To account for any water lost from seepage through the bottom of the pots, we separately "added back" that estimated amount twice a day, at dawn and in the evening.

**Photosynthetic parameters and measurement of WUE_I:** The net photosynthetic rate ($P_N$), stomatal conductance ($g_s$), and transpiration rate ($E$) were evaluated from the upper-most fully expanded leaves, using a combined open gas-exchange system (*LI-6400-40, LI-COR, Inc.*, Lincoln, NE, USA). Photosynthetic photon flux density was maintained at 1,000 mol m$^{-2}$ s$^{-1}$ from an internal red/blue LED light source. $CO_2$ flow was fixed at 400 μmol s$^{-1}$. The leaf temperature was maintained at 33 to 35°C, and relative humidity was 40 to 50% during the experimental period. Values for those parameters were determined from four samples per treatment, between 9:00 h and 11:00 h. WUE_I was calculated by the following equation:

$$WUE_I = P_N/g_s$$

**Calculations of growth, biomass, and WUE_L:** Shoot heights were recorded from the grafting point to the terminal bud of the main stem. Trunk diameters for both scion and stock materials were measured with a digital micrometer (to the nearest 0.001 mm) at 2 cm away from the grafting point. After the plants were harvested, they were divided into root, stock-stem, scion-stem, and leaf portions, then oven-dried for at least 48 h at 80°C before being weighed. In addition, at the beginning of ADI, some plants were harvested from the drought and well-watered treatments. They were divided into shoot and root portions, then separately oven-dried and weighed to determine a baseline for initial dry biomass. The root-to-shoot ratio (R/S) was computed as root mass divided by shoot mass, on a dry-mass basis.

WUE_L was calculated by the following equation:

$$WUE_L = DBG/ET$$

where DBG (final dry biomass minus initial dry biomass) was used to describe the gain in dry biomass over the experimental period. The calculation for evapotranspirational loss, ET, was based on an equation from Songsri *et al.* 2009:

$$ET = I + (Mi - Mf) - D - R$$

In the original equation, I represents the total amount of irrigation applied; Mi and Mf were the starting and final soil moisture contents, respectively; D was the amount of water lost by soil drainage; and R was the amount lost to surface runoff. However, we did not detect any drainage or runoff, and values for Mi and Mf were similar among our treatment types, so we could ignore

those variables here. Thus, we considered ET to be equivalent to I, or the total amount of irrigation water applied in each treatment.

Data for total leaf area were collected with an *Epson Perfection V700* Photo Scanner *(Seiko Epson Corp,* Nagano, HU, Japan) and were analyzed by *Win RHIZO* software *(Package V5.0, Regent Instruments, Inc.,* Quebec, QC, Canada).

**Sap flow** was measured by a stem heat balance method. Two types of Dynagage Sap Flow Sensors *(Flow 32-K1, Dynamax, Inc.,* Houston, TX, USA) were used: (*1*) SGA 9,

having sensitivity within $9 \pm 1$ mm of the measured trunk diameter; and (*2*) SGA5, with a sensitivity range of 5 to 7 mm. Stem sap flow was determined at a point 5 cm from the graft.

**Statistical analyses**: All data were analyzed with *Excel* and *Origin 8.0* software. One-way *ANOVA* and comparisons between means were conducted along with *Fisher* LSD tests at *P*<0.05. Significant correlations among variables were determined by *Pearson*'s correlation coefficient tests at *P*<0.05.

## Results

**Photosynthetic parameters and WUE**: Well-watered control plants had higher rates of $P_N$, $E$, and $g_s$ than did those exposed to drought conditions (Fig. 1). Although values for $P_N$, $E$, and $g_s$ decreased in water-stressed plants over time, those that received subsequent ADI treatment showed higher $P_N$, $E$, and $g_s$ values than even the control plants did when FC was 70%. Likewise, those parameters were similar between ADI- and drought-treated plants at 55% FC. Although changes in $WUE_I$ were more complex, the values from control and drought-stressed plants initially rose in the first 10 d before decreasing afterward. For plants under ADI treatment, $WUE_I$ was lowest when the soil water content was 70% FC; the

opposite was found when FC was reduced. Average values for $P_N$, $E$, $g_s$, and $WUE_I$ were 17.0 $\mu$mol($CO_2$) $m^{-2}$ $s^{-1}$, 7.18 mmol($H_2O$) $m^{-2}$ $s^{-1}$, 0.22 mol($H_2O$) $m^{-2}$ $s^{-1}$, and 85.1 $\mu$mol $mol^{-1}$, respectively, under control conditions. This compared with 9.8 $\mu$mol($CO_2$) $m^{-2}$ $s^{-1}$, 2.99 mmol($H_2O$) $m^{-2}$ $s^{-1}$, 0.12 mol($H_2O$) $m^{-2}$ $s^{-1}$, and 100.0 $\mu$mol $mol^{-1}$, respectively, for drought-stressed plants, and 14.2 $\mu$mol($CO_2$) $m^{-2}$ $s^{-1}$, 5.64 mmol($H_2O$) $m^{-2}$ $s^{-1}$, 0.21 mol($H_2O$) $m^{-2}$ $s^{-1}$, and 90.4 $\mu$mol $mol^{-1}$, respectively, for ADI-treated plants. Control plants had the highest $WUE_L$ (3.33 g $kg^{-1}$), followed by ADI (1.71 g $kg^{-1}$) and drought-stressed plants (1.50 g $kg^{-1}$) (Table 1).
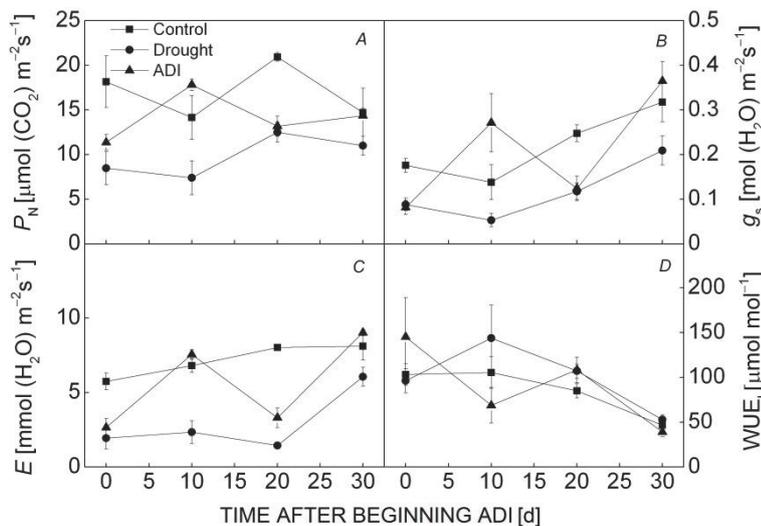


Fig. 1. Net photosynthetic rate, $P_N$ (*A*); stomatal conductance, $g_s$ (*B*); leaf transpiration $E$ (*C*); and instantaneous water-use efficiency, $WUE_I$ (*D*) under well-watered control, drought, and alternate deficit irrigation after imposing long-term water stress during the experimental period. Data are the mean $\pm$ SD (*n* = 4).

Table 1. Plant growth parameters, total amount of irrigation water applied (irrigation), and long-term water-use efficiency ($WUE_L$) under well-watered control, drought, or alternate deficit irrigation (ADI) treatment when following long-term water stress. Data are the mean $\pm$ SD (*n* = 4). Values not followed by *the same letter* within a column are significantly different at *P*<0.05 (LSD test).

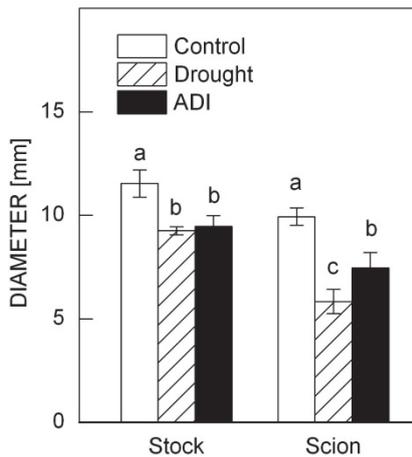| Parameter | Control | Drought | ADI |
|---|---|---|---|
| Shoot height [cm] | $109.86 \pm 4.02^a$ | $52.00 \pm 8.42^b$ | $43.65 \pm 8.45^b$ |
| Total leaf area [cm$^2$] | $1{,}437.05 \pm 289.68^a$ | $608.56 \pm 64.92^b$ | $858.30 \pm 43.14^b$ |
| Dry biomass gain [g] | $48.62 \pm 3.43^a$ | $7.61 \pm 1.65^c$ | $15.74 \pm 1.09^b$ |
| Irrigation [kg] | 14.6 | 5.1 | 9.2 |
| $WUE_L$ [g $kg^{-1}$] | $3.33 \pm 0.23^a$ | $1.50 \pm 0.26^c$ | $1.71 \pm 0.18^b$ |

Fig. 2. Stock and scion diameters under well-watered control, drought, or alternate deficit irrigation treatment after imposing long-term water stress. Data are the mean ± SD (*n* = 4). Values not followed by *the same letter* for each organ type are significantly different at *P*<0.05.



**Growth performance among treatment types**: Compared with the well-watered control, drought-stressed plants had significantly less new height growth as well as smaller rootstock and scion diameters (Fig. 2, Table 1). Plants receiving ADI treatment showed better performance than drought-stressed plants when shoot development, rootstock diameter, total leaf area, and DBG were considered. Scion diameters were also significantly larger for ADI versus drought but significantly smaller when compared with control plants.

**Dry biomass**: Under both drought treatment and ADI, plants accumulated statistically less dry mass in their roots, stock and scion stems, and leaves, as well as lower total biomass, compared with the well-watered control (Fig. 3). However, the introduction of ADI did have a positive effect on dry mass parameters, and was linked with significant improvements in total dry biomass and stock-stem mass. The trend in R/S was drought > ADI > control, with those differences also being significant.
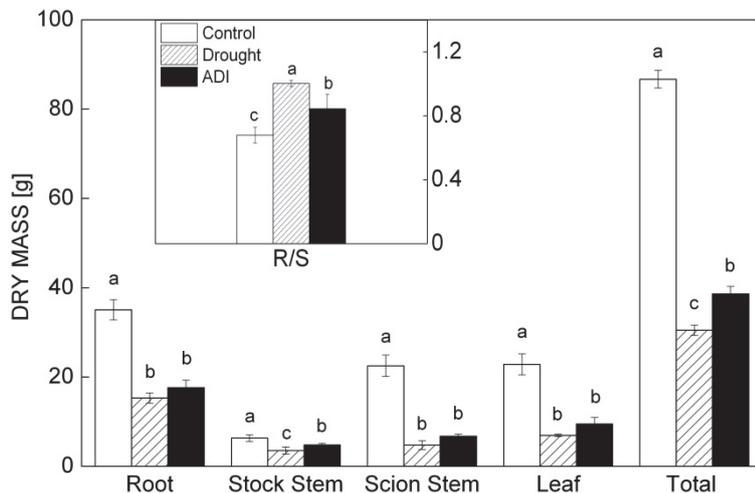
Fig. 3. Root dry mass, stock-stem dry mass, scion-stem dry mass, leaf dry mass, total dry biomass, and root-to-shoot ratio (R/S) under well-watered control; drought; or alternate deficit irrigation after imposing long-term water stress. Data are the mean ± SD (*n* = 4). Values not followed by *the same letter* for each organ type are significantly different at *P*<0.05.

**Sap flow *vs.* the total amount of irrigation water applied**: Sap flow from drought-stressed plants increased from 0 to 100 g during the experimental period, with those values being much lower than the ones calculated for the control (Fig. 4). Sap flow was more abundant in ADI plants than in drought-stressed plants, even though the soil water content was similar between those treatments for 10 to 20 d. Values for the control, drought, and ADI were 9,594.5 g; 1,020.8 g; and 3,315.4 g, respectively; daily average sap flow (SPd) was 319.8 g, 34.0 g, and 110.5 g respectively. The per-plant amount of irrigation applied in the control, drought, and ADI treatments was 14.6 kg, 5.1 kg and 9.2 kg, respectively – levels that were always higher than the total amount of sap flow computed for individual treatment types. The total amount of water applied was 5.0 kg, 4.1 kg, and 5.9 kg higher than the values determined for total sap flow in plants from the

control, drought, and ADI treatments, respectively.

**Relationships among $P_N$, $g_s$, $WUE_I$, total amount of irrigation water applied, $WUE_L$, DBG, and SPd**: Table 2 shows the interactions among parameters when the three watering treatments were contrasted. For example, $P_N$, irrigation (I), DBG, and SPd had highly significant and positive linear correlations with $WUE_L$. Although $WUE_L$ was most significantly and negatively correlated with $WUE_I$, it was significantly and positively correlated with $g_s$. $WUE_I$ was also negatively correlated with the other parameters. Finally, under the three treatments, SPd was correlated significantly and positively with $WUE_L$, I, and DBG, less so with $g_s$, and negatively with $WUE_I$. The plot of sap flow values against $g_s$ confirmed the close relationship between them under the different watering regimes (Fig. 5).

## Discussion

When ADI was introduced after long-term drought stress, such treatment induced better performance with regard to root and stem masses compared with values recorded from drought-exposed plants. This was especially true for total dry biomass and rootstock dry mass as more water was applied. O'Connell and Goodwin (2007) have shown that various irrigation methods influence the size and yield of 'Pink Lady' fruits. However, not all species exhibit the same sensitivity to drought, perhaps due to inter- and intraspecific variations in their mechanisms for controlling transpiration and their relative susceptibility to soil water deficits, as observed with grapevine (Schultz 2003) and tea plants (Netto *et al.* 2010). Our well-watered 'Pink Lady' trees had the lowest R/S (0.68) compared with 0.84 for ADI plants and 1.00 for drought-stressed plants. That ratio has also been shown to increase under water stress in *Populus* species (Yin *et al.* 2005). The improvement in that ratio associated with our drought treatment indicated that the deep, thick root systems of those plants, and their higher root densities, were important factors contributing to their drought-avoidance mechanisms (Kwak *et al.* 2011).

On the leaf scale, WUE is represented as net photosynthetic rate divided by either transpiration rate ($P_N/E$) or stomatal conductance ($P_N/g_s$); on the plant scale, WUE is defined as the ratio of biomass produced to water consumed. Our results indicated that both long- and short-term WUE were affected by the three watering treatments (Fig. 1*D*, Table 1). Whereas $WUE_L$ showed significant and positive linear correlations with I, SPd, and DBG, the parameter of $WUE_I$ had significantly negative linear correlations with $WUE_L$, I, and DBG. These results suggest that 'Pink Lady' apple has both a high consumption of water but also high WUE. This conclusion is similar to that made by Liu *et al.* (2012) for the same cultivar, where plants under drought had lower $WUE_L$ values than well-watered trees. We can also propose that, under such stress conditions, plants may employ two different water-use strategies: higher drought tolerance and conservative water use *vs.* lower drought
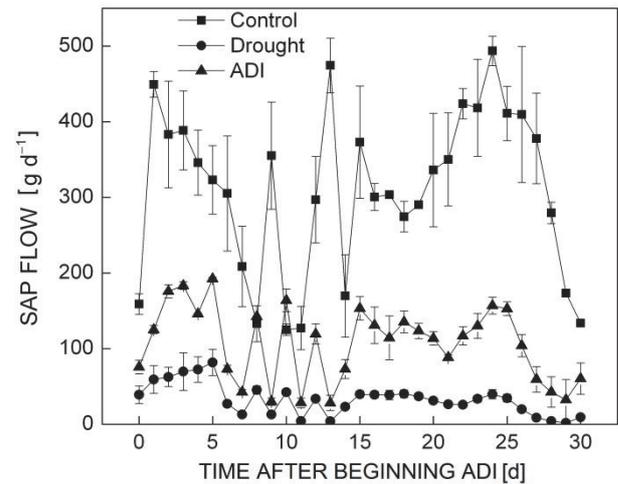


Fig. 4. Daily changes in sap flow under well-watered control; drought; and alternate deficit irrigation (ADI) after imposing long-term water stress. Data are the mean ± SD (*n* = 4).
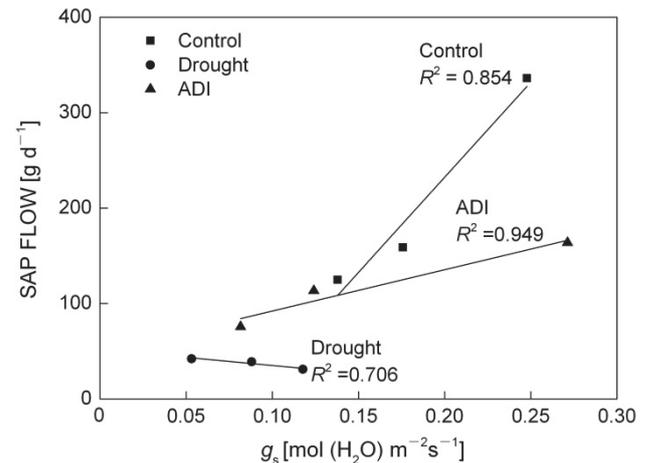


Fig. 5. Relationship between sap flow and stomatal conductance ($g_s$) under three watering treatments [well-watered control, drought, and alternate deficit irrigation (ADI) after imposing long-term water stress].

Table 2. Linear correlations (*r* values) among net photosynthesis ($P_N$), stomatal conductance ($g_s$), instantaneous water-use efficiency ($WUE_I$), total amount of irrigation water applied (irrigation), long-term water-use efficiency ($WUE_L$), dry biomass gain (DBG), and daily sap flow (SPd), under three watering treatments. $|r| > 0.7$, most-significant correlation; $0.4 < |r| < 0.7$, significant correlation; $|r| < 0.4$, least-significant correlation; *, significant at $P<0.05$. *n* = 16.

| | $P_N$ | $g_s$ | $WUE_I$ | Irrigation | $WUE_L$ | DBG | SPd |
|---|---|---|---|---|---|---|---|
| $P_N$ | 1 | | | | | | |
| $g_s$ | 0.949537[*] | 1 | | | | | |
| $WUE_I$ | −0.99905[*] | −0.96229* | 1 | | | | |
| Irrigation | 0.938397[*] | 0.782656[*] | −0.92246[*] | 1 | | | |
| $WUE_L$ | 0.925385[*] | 0.759802[*] | −0.90801[*] | 0.999355[*] | 1 | | |
| DBG | 0.896637[*] | 0.712512[*] | −0.87651[*] | 0.994403[*] | 0.997555[*] | 1 | |
| SPd | 0.615486[*] | 0.337219 | −0.58059[*] | 0.849921[*] | 0.868292[*] | 0.900833[*] | 1 |

tolerance and prodigal water use (Chirino *et al.* 2011). Our results indicate that 'Pink Lady' apple utilizes the latter strategy in coping with drought.

The cultural practice of ADI is one means for manipulating water-saving capacity in plants. Here, we applied this method after long-term moisture stress to improve $WUE_L$, shoot development, and DBG. Morphological and anatomical differences, both inter- and intra-specific, can lead to different patterns of WUE, $g_s$, $E$, and $P_N$ (Rodríguez-Gamir *et al.* 2010). For example, we found that 'Pink Lady' apple showed less efficiency under drought conditions (Table 1) while many other apple cultivars, *e.g.*, 'Qingguan', have higher values for WUE when water-stressed (Liu *et al.* 2012).

Many fruit trees comprise two or three different segments – scion, rootstock, and mid-rootstock. Interactions among those components affect WUE, photosynthesis, and overall growth. For example, Soar *et al.* (2006) have reported that rootstock genotype has a significant impact on scion gas exchange, water status, canopy growth, and yield. Likewise, Tandonnet *et al.* (2010) have found that the scion genotype for grape vines has a major effect on early shoot growth, root development, and biomass allocation. Finally, Ma *et al.* (2010) have demonstrated that $WUE_L$ in *Malus* rootstock can potentially be improved without necessarily reducing growth rates. There-fore, the judicious selection of scion–rootstock combinations can play a role in enhancing WUE.

As determined by a weighing method, the total amount of water lost from a plant *via* evapotranspiration was considerably larger than the total amount of sap that flowed through the same plant (Fig. 4, Table 1). Our results are not consistent with those reported in a study of young apricot trees by Alarcón *et al.* (2000). There, values for sap flow were equal to those calculated for transpiration when measured by a weighing-balance method. In our experiments, soil evaporation was unavoidable, and the shorter the irrigation interval, the greater the rate of evaporation. In fact, Cooper *et al.* (1983) have demonstrated that, when growing a crop, evaporation from the soil surface can account for 30% to 60% of all water used, *i.e.*, through evapotranspiration. Values for sap flow provide a continuous and automatic record of trends in plant transpiration even if those values are not similar. For example, when the onset of a water deficit is rapid or waterlogging occurs, sap flow and transpiration rates may be dissimilar (Alarcón *et al.* 2000, Nicolás *et al.* 2005). Finally, if we had used plastic film instead of sand to prevent surface evaporation, values for sap flow may have matched those for the amount of water irrigation applied.

## References

Alarcón, J.J., Domingo, R., Green, S.R., Sánchez-Blanco, M.J., Rodríguez, P., Torrecillas, A.: Sap flow as an indicator of transpiration and the water status of young apricot trees. – Plant Soil **227**: 77-85, 2000.

Bindon, K., Dry, P., Loveys, B.: Influence of partial rootzone drying on the composition and accumulation of anthocyanins in grape berries (*Vitis vinifera* cv. Cabernet Sauvignon). – Aust. J. Grape Wine Res. **14**: 91-103, 2008.

Chaves, M.M., Santos, T.P., Souza, C.R., Ortuño, M.F., Rodrigues, M.L., Lopes, C.M., Maroco, J.P., Pereira, J.S.: Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. – Ann. Appl. Biol. **150**: 237-252, 2007.

Chaves, M.M., Zarrouk, O., Francisco, R., Costa, J.M., Santos, T., Regalado, A.P., Rodrigues, M.L.: Grapevine under deficit irrigation: hints from physiological and molecular data. – Ann. Bot. **105**: 661-676, 2010.

Chirino, E., Bellot, J., Sánchez, J.: Daily sap flow rate as an indicator of drought avoidance mechanisms in five Mediterranean perennial species in semi-arid southeastern Spain. – Trees **25**: 1-14, 2011.

Cooper, P.J.M., Keatinge, J.D.H., Hughes, G.: Crop evapotranspiration – a technique for calculation of its components by field measurements. – Field Crops Res. **7**: 299-312, 1983.

Cui, N., Du, T., Kang, S., Li, F., Zhang, J., Wang, M., Li, Z.: Regulated deficit irrigation improved fruit quality and water use efficiency of pear-jujube trees. – Agr. Water Manage. **95**: 489-497, 2008.

Egilla, J.N., Davies, F.T., Boutton, T.W.: Drought stress influences leaf water content, photosynthesis, and water-use efficiency of *Hibiscus rosa-sinensis* at three potassium concentrations. – Photosynthetica **43**: 135-140, 2005.

Elias, F., Auxiliadora, S.M.: Deficit irrigation for reducing agricultural water use. – J. Exp. Bot. **58**: 147-159, 2007.

García, J.G., Martínez-Cutillas, A., Romero, P.: Financial analysis of wine grape production using regulated deficit irrigation and partial-root zone drying strategies. – Irrig. Sci. **30**: 179-188, 2012.

Kwak, M.J., Lee, S.H., Woo, S.Y.: Growth and anatomical characteristics of different water and light intensities on cork oak (*Quercus suber* L.) seedlings. – Afr. J. Biot. **10**: 10964-10979, 2011.

Liu, B., Cheng, L., Ma, F., Zou, Y., Liang, D.: Growth, biomass allocation and water use efficiency of 31 apple cultivars grown under two water regimes. – Agrofor. Syst. **84**: 117-129, 2012.

Ma, X., Ma, F., Li, C., Mi, Y., Bai, T., Shu, H.: Biomass accumulation, allocation, and water-use efficiency in 10 Malus rootstocks under two watering regimes. – Agroforest. Syst. **80**: 283-294, 2010.

Massonnet, C., Costes, E., Rambal, S., Dreyer, E., Regnard, J.L.: Stomatal regulation of photosynthesis in apple leaves: evidence for different water-use strategies between two cultivars. – Ann. Bot. **100**: 1347-1356, 2007.

Netto, L.A., Jayaram, K.M., Puthur, J.T.: Clonal variation of tea [*Camellia sinensis* (L.) O. Kumtze] in countering water deficiency. – Physiol. Mol. Biol. Plants **16**: 359-367, 2010.

Nicolás, E., Torrecillas, A., Dell'Amico, J., Alarcón, J. J.: The effect of short-term flooding on the sap flow, gas exchange and hydraulic conductivity of young apricot trees. – Trees **19**: 51-57, 2005.

O'Connell, M.G., Goodwin, I.: Responses of 'Pink Lady' apple to deficit irrigation and partial rootzone drying: physiology, growth, yield, and fruit quality. – Aust. J. Agr. Res. **58**: 1068-1076, 2007.

Ortuño, M., García-Orellana, Y., Conejero, W., Ruiz-Sánchez, M., Alarcón, J., Torrecillas, A.: Stem and leaf water potentials, gas exchange, sap flow, and trunk diameter fluctuations for detecting water stress in lemon trees. – Trees **20**: 1-8, 2006.

Rodríguez-Gamir, J., Intrigliolo, D., Primo-Millo, E., Forner-Giner, M.: Relationships between xylem anatomy, root hydraulic conductivity, leaf/root ratio and transpiration in citrus trees on different rootstocks. – Physiol. Plant. **139**: 159-169, 2010.

Sadras, V.O.: Does partial root-zone drying improve irrigation water productivity in the field? A meta-analysis. – Irrig. Sci. **27**: 183-190, 2009.

Schultz, H.R.: Differences in hydraulic architecture account for near-isohydric and anisohydric behaviour of two field-grown *Vitis vinifera* L. cultivars during drought. – Plant Cell Environ. **26**: 1393-1405, 2003.

Soar, C.J., Dry, P.R., Loveys, B.R.: Scion photosynthesis and leaf gas exchange in *Vitis vinifera* L. cv. Shiraz: Mediation of rootstock effect via xylem sap ABA. – Aust. J. Grape Wine Res. **12**: 82-96, 2006.

Songsri, P., Jogloy, S., Holbrook, C.C., Kesmala, T., Vorasoot, N., Akkasaeng, C., Patanothai, A.: Association of root, specific leaf area and SPAD chlorophyll meter reading to water use efficiency of peanut under different available soil water. – Agr. Water Manage. **96**: 790-798, 2009.

Tandonnet, J.P., Cookson, S.J., Vivin, P., Ollat, N.: Scion genotype controls biomass allocation and root development in grafted grapevine. – Aust. J. Grape Wine Res. **16**: 290-300, 2010.

Yin, C., Wang, X., Duan, B., Luo, J., Li, C.: Early growth, dry matter allocation and water use efficiency of two sympatric *Populus* species as affected by water stress. – Environ. Exp. Bot. **53**: 315-322, 2005.

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