Alternate partial root-zone irrigation with high irrigation frequency improves root growth and reduces unproductive water loss by apple trees in arid north-west China

Shaoqing DU\(^1\), Ling TONG (✉)\(^1\), Shaozhong KANG\(^1\), Fusheng LI\(^2\), Taisheng DU\(^1\), Sien LI\(^1\), Risheng DING\(^1\)

1 Center for Agricultural Water Research in China, China Agricultural University, Beijing 100083, China
2 College of Agriculture, Guangxi University, Nanning 530005, China

Abstract
Alternate partial root-zone irrigation (APRI) can improve water use efficiency in arid areas. However, the effectiveness and outcomes of different frequencies of APRI on water uptake capacity and physiological water use have not been reported. A two-year field experiment was conducted with two irrigation amounts (400 and 500 mm) and three irrigation methods (conventional irrigation, APRI with high and low frequencies). Root length density, stomatal conductance, photosynthetic rate, transpiration rate, leaf water use efficiency, midday stem and leaf water potentials were measured. The results show that in comparison with conventional irrigation, APRI with high frequency significantly increased root length density and decreased water potentials and stomatal conductance. No differences in the above indicators between the two APRI frequencies were detected. A significantly positive relationship between stomatal conductance and root length density was found under APRI. Overall, alternate partial root-zone irrigation with high frequency has a great potential to promote root growth, expand water uptake capacity and reduce unproductive water loss in the arid apple production area.

Keywords
alternate partial root-zone irrigation, apple tree, leaf water use efficiency, root length density, stomatal conductance, water potential

1 Introduction

China has the largest apple production area in the world and accounts for 50% of global production capacity. Annual apple production increased from 800 kt in 1970 to 38 Mt in 2012, and is expected to be 51 Mt by 2020. Arid north-west China is an important high quality apple production area because of ample sunlight and heat, a large difference between day and night temperatures and a dry climate\(^1\). However, water resource availability limits the expansion of production in this area, as does the risk of climate change effects. Therefore it is urgent to enhance irrigation water use efficiency by improving irrigation methods and reducing irrigation amounts\(^2\).

Under conventional irrigation with large irrigation volumes and long irrigation intervals, there is a alternation of excess water supply and water deficit stress, which results in increasing stomatal conductance and luxury transpiration for a short time after irrigation, followed by reduced water potential and photosynthesis before the next irrigation\(^3\). Previous studies indicated that promoting root growth, reducing luxury transpiration and regulating stomatal movement are important approaches to improve water use efficiency of fruit trees\(^4,5\). Stomata are the channels for flux exchange between trees and the atmosphere, and adjusting stomatal opening and closing regulates water loss through transpiration\(^6\).

Stem and leaf water potentials are important indicators to characterize water status of fruit trees, as these determine water movement\(^7,8\). When water content of a tree is reduced, the decreased water potential and the increased tension of xylem result in the cavitation and embolization of xylem, which may reduce water transport capacity and ultimately decrease stomatal conductance\(^9\). Furthermore, the reduction of stem and leaf water potentials results in the decrease in leaf stomatal conductance under conventional irrigation\(^10–12\).

However, the variation of stomatal conductance is not only affected by water potential, but is also related to the ion concentration in root signals\(^13,14\). When water deficit stress occurs, the root system can send chemical signals to reduce leaf stomatal conductance and luxury transpiration\(^15\). Meanwhile, moderate water deficit stress may promote root growth and improve water uptake...
capacity\textsuperscript{[16]}. According to the above- and below-ground balance theory\textsuperscript{[17]}, fruit trees can transfer more photosynthates into roots under moderate water deficit stress, while more photosynthates will be transported to leaves and fruits under adequate water supply\textsuperscript{[18]}. Moreover, a significant linear correlation has been found between stomatal conductance and root length density under conventional irrigation\textsuperscript{[19]}, which better reflects the relationship between above-ground and below-ground water status.

Alternate partial root-zone irrigation (APRI) is an innovative irrigation method, which can reduce stomatal conductance and improve water use efficiency\textsuperscript{[14,20]}. However, the effectiveness and outcomes of different frequencies of APRI on root water uptake capacity and physiological water use have not been reported and need investigation. Therefore, the objectives of this study were (1) to evaluate the impact of APRI with different irrigation frequencies on root length density, stomatal conductance, photosynthetic rate, transpiration rate, leaf water use efficiency, and midday stem and leaf water potentials in apple trees in arid north-west China, and (2) to analyze the relationship between stomatal conductance and root length density to understand the mechanism of efficient water use under this system.

2 Materials and methods

2.1 Experimental site and meteorological parameters

Field experiments were conducted during 2013 and 2014 in a field of about 0.5 hm\textsuperscript{2} (68 m × 66 m) with 170 trees. Experimental apple trees (\textit{Malus domestica} Borkh. cv Golden Delicious) were planted in 1981 at a row spacing of 6 m and plant spacing of 4 m. Eighteen trees of similar size with no disease or pests were selected to reduce tree damage and workload (Table 1). There were six treatments, including two irrigation amounts and three irrigation methods, and each treatment had three replicates. The two irrigation amounts were 400 and 500 mm, and three irrigation methods were (1) conventional irrigation, irrigated 4 times over the whole growth season (CI), (2) APRI with high irrigation frequency (PRIH), irrigated 8 times for two subplots alternately, and (3) APRI with low irrigation frequency (PRI\textsubscript{L}), irrigated 4 times for two subplots alternately. Irrigation was applied by border irrigation through

*Fig. 1*  Seasonal variations of net radiation ($R_n$) and precipitation (Precip) over the entire 2013 and 2014 growth seasons
irrigation pipelines from the well in the apple orchard and the irrigation amount was monitored by water meter linked to the pipelines. Irrigation times, quota and date are shown in Table 2.

To avoid the exchange of water and nutrients between neighboring subplots, impermeable film (1.5 m deep, 3.0 m wide and 3.0 m long) was installed around the trees with a ridge (0.3 m high) formed at ground level on 4

| Irrigation amount/mm | Irrigation method | Trunk diameter/mm | Bark depth/mm | Radius of sapwood/mm | Radius of heartwood/mm |
|----------------------|-------------------|-------------------|---------------|----------------------|------------------------|
| 400                  | CI                | 269               | 6.0           | 128                  | 76                     |
|                      |                   | 251               | 6.3           | 111                  | 45                     |
|                      |                   | 263               | 7.0           | 142                  | 48                     |
|                      | PRIH              | 267               | 5.9           | 126                  | 70                     |
|                      |                   | 279               | 7.1           | 135                  | 75                     |
|                      |                   | 245               | 5.8           | 123                  | 61                     |
|                      | PRIL              | 252               | 6.0           | 120                  | 68                     |
|                      |                   | 287               | 7.9           | 129                  | 58                     |
|                      |                   | 239               | 6.0           | 119                  | 62                     |
| 500                  | CI                | 247               | 5.0           | 118                  | 67                     |
|                      |                   | 275               | 8.0           | 141                  | 65                     |
|                      |                   | 259               | 5.3           | 135                  | 55                     |
|                      | PRIH              | 266               | 6.2           | 126                  | 54                     |
|                      |                   | 258               | 6.0           | 125                  | 45                     |
|                      |                   | 281               | 7.3           | 131                  | 55                     |
|                      | PRIL              | 263               | 5.6           | 125                  | 44                     |
|                      |                   | 279               | 7.5           | 121                  | 54                     |
|                      |                   | 249               | 6.4           | 105                  | 48                     |
| Average              |                   | 263               | 6.4           | 126                  | 58                     |
| Maximum              |                   | 287               | 8.0           | 141                  | 76                     |
| Minimum              |                   | 245               | 5.0           | 105                  | 44                     |

Note: CI, conventional irrigation; PRIH, alternate partial root-zone irrigation with high irrigation frequency; PRIL, alternate partial root-zone irrigation with low irrigation frequency.

| Year | Amount/mm | Method | No. of times | Quota/mm | Detail                                      | Date                      |
|------|-----------|--------|--------------|----------|---------------------------------------------|---------------------------|
| 2013 | 400       | CI     | 4            | 100.0    | 26 April, 31 May, 27 June, 1 August         |                           |
|      |           | PRIH   | 8            | 50.0     | 26 April, 13 May, 31 May, 19 June, 27 June, 14 July, 1 August |                           |
|      |           | PRIL   | 4            | 100.0    | 26 April, 31 May, 27 June, 1 August         |                           |
|      | 500       | CI     | 4            | 125.0    | 26 April, 31 May, 27 June, 1 August         |                           |
|      |           | PRIH   | 8            | 62.5     | 26 April, 13 May, 31 May, 19 June, 27 June, 14 July, 1 August |                           |
|      |           | PRIL   | 4            | 125.0    | 26 April, 31 May, 27 June, 1 August         |                           |
| 2014 | 400       | CI     | 4            | 100.0    | 25 April, 5 June, 13 July, 7 August        |                           |
|      |           | PRIH   | 8            | 50.0     | 25 April, 24 May, 5 June, 26 June, 13 July, 29 July, 7 August, 31 August |                           |
|      |           | PRIL   | 4            | 100.0    | 25 April, 5 June, 13 July, 7 August        |                           |
|      | 500       | CI     | 4            | 125.0    | 25 April, 5 June, 13 July, 7 August        |                           |
|      |           | PRIH   | 8            | 62.5     | 25 April, 24 May, 5 June, 26 June, 13 July, 29 July, 7 August, 31 August |                           |
|      |           | PRIL   | 4            | 125.0    | 25 April, 5 June, 13 July, 7 August        |                           |

Note: CI, conventional irrigation; PRIH, alternate partial root-zone irrigation with high irrigation frequency; PRIL, alternate partial root-zone irrigation with low irrigation frequency.
April, 2013 (Fig. 2). In addition, to avoid the movement of water and nutrients between the wet and dry areas, the APRI plots were also divided into two equal subplots by impermeable film (0.5 m deep) with a ridge (0.3 m high) formed at ground level (Fig. 2). The orchard was fertilized annually with 440 kg·hm⁻² N, 200 kg·hm⁻² P₂O₅ and 150 kg·hm⁻² K₂O as urea (N 46%), diammonium phosphate (P₂O₅ 45%, N 17%) and potassium magnesium sulfate (K₂O 24%), respectively. In addition, weeds were controlled manually or with herbicides, and pests with pesticides as needed.

2.3 Measurements

2.3.1 Root length density

The roots samples were taken using a root auger (10 cm × 10 cm). Samples were taken to 1.5 m deep at 0.1 m intervals. Over the whole growth season, one row of 14 sites from east to west of the subplot were taken in each growth stage (Fig. 2). After sieving the soil sample, the roots of < 2 mm in diameter were collected and washed with tap water. The clean roots were arranged regularly on transparent plexiglass plates and scanned to give Tagged Image File Format images (Epson Perfection V700 Photo, Seiko Epson Corp., Nagano, Japan) of 300 dpi for further analysis. The image files were analyzed by WinRHIZO image analysis software (Regent Instrument Inc., Quebec, QC, Canada) to obtain root length density. After roots were removed, the soil was used to backfill sampling holes. In addition, to avoid any sampling effect on tree growth, different replicate trees were sampled in 2013 and 2014.

2.3.2 Stomatal conductance, photosynthetic rate, transpiration rate and leaf water use efficiency

Stomatal conductance, and photosynthetic and transpiration rates were measured using an LI-6400 portable photosynthesis system (LI-COR Biosciences, Lincoln, NE, USA) with a standard chamber. The measurements were taken on four mature leaves of similar size and age from both south and north sides of each treatment at 12:00 on typical sunny days. During the whole growth season, four measurements were taken at the same time as the soil sampling. The data logger of the LI-6400 recorded stomatal conductance, and photosynthetic and transpiration rates immediately after measurement. In addition, leaf water use efficiency was calculated as:

\[ WUE_{\text{leaf}} = \frac{P_n}{T_r} \] (1)

where \( WUE_{\text{leaf}} \) is leaf water use efficiency (mmol CO₂·mol⁻¹ H₂O), \( P_n \) is photosynthetic rate (μmol CO₂·m⁻²·s⁻¹), and \( T_r \) is transpiration rate (mmol H₂O·m⁻²·s⁻¹).

2.3.3 Midday stem and leaf water potentials

Three hours before the measurement, two mature leaves of similar size and age from both south and north sides near the tree stem were enclosed in opaque plastic bags covered with aluminum foil, and water potentials of the leaves were measured immediately at 12:00 using a pressure chamber (SKPM 1400, Skye, UK). The midday water potentials of these leaves are considered to be equivalent to midday

---

**Fig. 2** Description of subplot isolation by impermeable film and ridges, and the positions of soil cores. To avoid the exchange of water and nutrients between neighboring subplots, impermeable film (1.5 m deep, 3.0 m wide and 3.0 m long) was installed around the trees with a ridge (0.3 m high) formed at ground level (A). In addition, to avoid the movement of water and nutrients between the wet and dry areas, the APRI plots were divided into two equal subplots by impermeable film (0.5 m deep) with a ridge (0.3 m high) formed at ground level (B).
stem water potentials\textsuperscript{[23]}. Midday leaf water potential was also measured for two mature leaves of similar size and age from both south and north sides immediately at 12:00. During the whole growth season, both stem and leaf water potentials were measured at time intervals of 5–7 d.

2.4 Statistics analysis

The general linear model procedure of the SAS software (SAS Institute, Cary, NC, USA) was used to perform analysis of variance with two- and three-way interactions for root length density, stomatal conductance, photosynthetic rate, transpiration rate, leaf water use efficiency, and midday stem and leaf water potentials with the main effects of year, irrigation amount and irrigation method. In addition, treatment means were compared by the least significant differences at $P < 0.05$.

3 Results and discussion

3.1 Root length density and stomatal conductance

Different irrigation methods and amounts had significant effects on root length density (Table 3), but no significant interactions were found for experiment year, irrigation method and amount. Therefore, root length density was further analyzed across experimental years, irrigation methods and irrigation amounts.

Root length density was significantly higher under PRI\textsubscript{H} than CI (Fig. 3a). Previous studies indicated that slight water deficit could promote root growth\textsuperscript{[14,24]}. Our results confirmed that frequent alternate drying and wetting under APRI stimulates root growth in apple trees (Fig. 3a). However, there was no significant difference in root length density between PRI\textsubscript{H} and PRI\textsubscript{L} (Fig. 3a). Slightly lower root length density under PRI\textsubscript{L} can be explained by reduced water uptake capacity of part of the root system in the dry area under PRI\textsubscript{L}, which suffers water deficit stress for a long time before the next watering interval. It further results in suberization of the root tip surface and the reduction in secondary roots until root death\textsuperscript{[20]}. In addition, significantly higher root length density with 500-mm irrigation compared to 400-mm irrigation (Fig. 3a) demonstrates that more photosynthates are transferred into the root system with 500-mm irrigation\textsuperscript{[25,26]}. In addition, there was no significant difference in root length density between the two years, which was probably due to lack of significant difference in root-zone soil water content\textsuperscript{[27]}.

There were significant effects of different irrigation methods and amounts on stomatal conductance (Table 3), while no significant interactive impact was found for experimental year, irrigation method and irrigation amount. Compared with CI, PRI\textsubscript{H} significantly reduced stomatal conductance (Table 3; Fig. 3b), which indicates that more abscisic acid can be produced under PRI\textsubscript{H} to

![Fig. 3](image)

**Table 3** Probabilities ($P$) of different treatments

| Source | DF | RLD | $g_s$ | $P_n$ | $T_r$ | WUE\textsubscript{leaf} | $\Psi_{stem}$ | $\Psi_{leaf}$ |
|--------|----|-----|-------|------|------|-----------------|-------------|-------------|
| IA     | 1  | < 0.001 | < 0.001 | < 0.001 | < 0.001 | 0.984 | < 0.001 | < 0.001 |
| IM     | 2  | < 0.05 | < 0.001 | < 0.001 | < 0.005 | 0.01 | 0.488 | < 0.001 |

Note: DF, degree of freedom; RLD, root length density; $g_s$, stomatal conductance; $P_n$, photosynthetic rate; $T_r$, transpiration rate; WUE\textsubscript{leaf}, leaf water use efficiency; $\Psi_{stem}$, midday stem water potential; $\Psi_{leaf}$, midday leaf water potential; IA, irrigation amount; IM, irrigation method. $P$ values were shown ($P < 0.05$, significant; $P < 0.01$, strongly significant; $P \geq 0.05$, not significant). The effects of Year and all interactions were non-significant.
decrease stomatal conductance, when the roots are under slight water deficit stress\cite{28,29}. Also, the moderate reduction in stomatal conductance under PR1H can decrease luxury transpiration\cite{27,30,31}. However, APRI with different irrigation frequencies had no significant impact on stomatal conductance (Fig. 3b). Furthermore, compared with 400-mm irrigation, 500-mm irrigation significantly enhanced stomatal conductance (Fig. 3b) because adequate water supply can generate turgor, which is beneficial for stomatal opening\cite{31,32}.

The stomatal conductance under different irrigation methods showed upward trends with the increase in root length density (Fig. 4). The significant linear relationship between stomatal conductance and root length density under APRI and CI indicates that root length density is an important factor for root water uptake capacity\cite{19}. Moreover, coordinating the relationship between stomatal conductance and root length density with different irrigation methods should first ensure the required transpiration during the normal photosynthetic processes, and then reduce unproductive water consumption of apple trees caused by excessive stomatal conductance\cite{33}.

3.2 Photosynthetic and transpiration rates, and leaf water use efficiency

Since no significant interactions were found for experimental year, irrigation method and irrigation amount for photosynthetic and transpiration rates, and leaf water use efficiency, the data were further analyzed across experimental years, irrigation methods and irrigation amounts, respectively (Table 3). There was no significant effect of the different irrigation methods on photosynthetic and transpiration rates, and leaf water use efficiency (Fig. 5), possibly because APRI does not significantly reduce carbon dioxide assimilation\cite{20}, but limits luxury transpiration without impact on apple tree physiological

Fig. 4 Relationship between stomatal conductance ($g_s$) and root length density (RLD) during the entire 2013 and 2014 growth seasons. CI, conventional irrigation; PR1H, alternate partial root-zone irrigation with high irrigation frequency; PR1L, alternate partial root-zone irrigation with low irrigation frequency; $R^2 = 0.80^{***}$, $R^2 = 0.61^{*}$, and $R^2 = 0.64^{*}$.  

Fig. 5 Photosynthetic rate ($P_n$) (a), transpiration rate ($T_r$) (b) and leaf water use efficiency (WUEleaf) (c) during the whole growth season as affected by year, irrigation amount and irrigation method. Bars labeled with different letters are significantly different ($P < 0.05$) and with the same letter are not significantly different ($P \geq 0.05$). Error bars indicate standard error of means. CI, conventional irrigation; PR1H, alternate partial root-zone irrigation with high irrigation frequency; and PR1L, alternate partial root-zone irrigation with low irrigation frequency.
processes\textsuperscript{[27]}. In addition, the slight reduction of photosynthetic and transpiration rates and the slight increase in leaf water use efficiency under APRI indicates that frequently alternating wetting and drying simulates roots, which would enhance the concentration of abscisic acid, and reduce unproductive water loss with the decrease in the vegetative growth\textsuperscript{[14,33]}. Compared with 400-mm irrigation, 500-mm irrigation significantly improved photosynthetic and transpiration rates (Fig. 5). This indicates that apple trees under 500-mm irrigation have sufficient water storage and suitable water status, which is advantageous for promoting leaf photosynthesis and transpiration, while apple trees under 400-mm irrigation are in water deficit stress, which will change cell structure and chloroplast hydration\textsuperscript{[3,34]}, and reduce enzymatic activity to further decrease leaf photosynthesis and transpiration\textsuperscript{[35]}. However, irrigation amount had no significant impact on leaf water use efficiency. This indicates that water percolation may have occurred with 500-mm irrigation due to the lower water holding capacity of the sandy soil in the orchard\textsuperscript{[36]}.  

3.3 Midday stem and leaf water potentials

No significant interactions were found for experimental year, irrigation method and amount for midday stem and leaf water potentials (Table 3). In comparison with CI, PRI\textsubscript{H} significantly reduced the midday stem and leaf water potentials from 0.05 to 0.10 MPa (Table 3; Fig. 6), which was lower than previously reported values\textsuperscript{[12,37]}. The primary reason for this could be the different irrigation methods and amounts used in those studies. For example, deficit irrigation could result in severe water deficit stress substantially reducing stem and leaf water potentials\textsuperscript{[37]}, while APRI could cause slight water deficit stress with only a slight reduction of stem and leaf water potentials (Fig. 6). In addition, the greater reduction of irrigation amount under APRI would also result in water deficit stress substantially decreasing water potential\textsuperscript{[12]}. In this study, the reduction of water potential was slight with APRI maintaining the same irrigation amount as CI (Fig. 3b). This further indicates that the trees under APRI did not suffer physiological water shortage (Fig. 6). In addition, no significant difference was found for midday stem and leaf water potentials between APRI at different irrigation frequencies (Fig. 6). In comparison with 400-mm irrigation, 500-mm irrigation significantly increased the midday stem and leaf water potentials (Fig. 6) due to abundant water storage and suitable water status of the trees under 500-mm irrigation\textsuperscript{[34]}.  

In summary, the promotion of root growth and the reduction of unproductive water loss are important approaches for saving water in arid areas\textsuperscript{[12]}. However, conventional irrigation always tends to increase luxury transpiration without obvious improvement in root water uptake capacity. In contrast, APRI with high irrigation frequency reduces tree luxury transpiration and enhances water use efficiency\textsuperscript{[27,31]}. In addition, the slight water deficit stress under APRI with high irrigation frequency would further promote root growth\textsuperscript{[14,33]}, expand water uptake capacity\textsuperscript{[24]} and reduce unproductive water consumption\textsuperscript{[30]}.  

4 Conclusions

Our results demonstrate that, compared with conventional irrigation of apple trees, APRI with high irrigation frequency significantly increased root length density, reduced midday stem and leaf water potentials and leaf stomatal conductance, while there was no significant impact of APRI irrigation frequency on the above parameters. However, a significantly positive relationship between stomatal conductance and root length density was found for APRI between the different irrigation frequen-
cies. Therefore, the mechanism of efficient water use in apple trees in arid areas could be that APRI with high irrigation frequency promotes root growth, enhances water uptake capacity and decreases unproductive water loss by apple trees. However, more research is required for a better understanding of efficient water management in the arid apple production area.

Acknowledgements This work was supported by the National Natural Science Foundation of China (51621061, 91425302) and the 111 Program of Introducing Talents of Discipline to Universities (B14002).

Compliance with ethics guidelines Shaoqing Du, Ling Tong, Shaozhong Kang, Fusheng Li, Taisheng Du, Sien Li, and Risheng Ding declare that they have no conflicts of interest or financial conflicts to disclose.

This article does not contain any studies with human or animal subjects performed by any of the authors.

References

1. Liu C, Kang S, Li F, Li S, Du T. Canopy leaf area index for apple tree using hemispherical photography in arid region. Scientia Horticulturae, 2013, 164: 610–615
2. Kang S, Hao X, Du T, Tong L, Su X, Lu H, Li X, Huo Z, Li S, Ding R. Improving agricultural water productivity to ensure food security in China under changing environment: from research to practice. Agricultural Water Management, 2017, 179: 5–17
3. Singh S, Angadi S V, Grover K, Begna S, Auld D. Drought response and yield formation of spring safflower under different water regimes in the semiarid Southern High Plains. Agricultural Water Management, 2016, 163: 354–362
4. Zhu L, Zhao P, Wang Q, Ni G, Niu J, Zhao X, Zhang Z, Zhao P, Gao J, Huang Y, Gu D, Zhang Z. Stomatal and hydraulic conductance and water use in a eucalypt plantation in Guangxi, southern China. Agricultural and Forest Meteorology, 2015, 202: 61–68
5. Hernandez-Santana V, Fernández J E, Rodriguez-Dominguez C M, Romero R, Díaz-Espejo A. The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit. Agricultural and Forest Meteorology, 2016, 218–219: 92–101
6. Bota J, Tomás M, Flexas J, Medrano H, Escaloná J M. Differences among grapevine cultivars in their stomatal behavior and water use efficiency under progressive water stress. Agricultural Water Management, 2016, 164: 91–99
7. Alcaras L M A, Rousseaux M C, Searles P S. Responses of several soil and plant indicators to post-harvest regulated deficit irrigation in olive trees and their potential for irrigation scheduling. Agricultural Water Management, 2016, 171: 10–20
8. Robles J M, Botía P, Pérez-Pérez J G. Subsurface drip irrigation affects trunk diameter fluctuations in lemon trees, in comparison with surface drip irrigation. Agricultural Water Management, 2016, 165: 11–21
9. Davies W J, Wilkinson S, Loveys B. Stomatal control by chemical signalling and the exploitation of this mechanism to increase water use efficiency in agriculture. New Phytologist, 2002, 153(3): 449–460
10. Atkinson C J, Policarpo M, Webster A D, Kingswell G. Drought tolerance of clonal Malus determined from measurements of stomatal conductance and leaf water potential. Tree Physiology, 2000, 20(8): 557–563
11. Whitehead D, Beadle C L. Physiological regulation of productivity and water use in Eucalyptus: a review. Forest Ecology and Management, 2004, 193(1–2): 113–140
12. Parviz H, Sepaskhah A R, Ahmadi S H. Physiological and growth responses of pomegranate tree (Punica granatum (L.) ev. Rabab) under partial root zone drying and deficit irrigation regimes. Agricultural Water Management, 2016, 163: 146–158
13. Blackman P G, Davies W J. Root to shoot communication in maize plants of the effects of soil drying. Journal of Experimental Botany, 1985, 36(1): 39–48
14. Davies W J, Zhang J. Root signals and the regulation of growth and development of plants in drying soil. Annual Review of Plant Physiology and Plant Molecular Biology, 1991, 42(1): 55–76
15. Siopongco J D L C, Sekiya K, Yamauchi A, Egdane J, Ismail A M, Wade J L. Stomatal responses in rainfed lowland rice to partial soil drying: Evidence for root signals. Plant Production Science, 2008, 11(1): 28–41
16. Zhang X, Shao L, Sun H, Chen S, Wang Y. Incorporation of soil bulk density in simulating root distribution of winter wheat and maize in two contrasting soils. Soil Science Society of America Journal, 2012, 76(2): 638–647
17. Wright J P, Naeem S, Hector A, Lehman C, Reich P B, Schmid B, Tilman D. Conventional functional classification schemes underestimate the relationship with ecosystem functioning. Ecology Letters, 2006, 9(2): 111–120
18. Vanninen P, Mäkelä A. Fine root biomass of Scots pine stands differing in age and soil fertility in southern Finland. Tree Physiology, 1999, 19(12): 823–830
19. Hayashi T, Yoshida T, Fujii K, Mitsuya S, Tsuji T, Okada Y, Hayashi E, Yamauchi A. Maintained root length density contributes to the waterlogging tolerance in common wheat (Triticum aestivum L.). Field Crops Research, 2013, 152: 27–35
20. Kang S, Zhang J. Controlled alternate partial root-zone irrigation: its physiological consequences and impact on water use efficiency. Journal of Experimental Botany, 2004, 55(407): 2437–2446
21. Liu C, Kang S, Li F, Li S, Du T, Tong L. Relationship between environmental factor and maximum daily stem shrinkage in apple tree in arid region of northwest China. Scientia Horticulturae, 2011, 130(1): 118–125
22. Liu C, Du T, Li F, Kang S, Li S, Tong L. Trunk sap flow characteristics during two growth stages of apple tree and its relationships with affecting factors in an arid region of northwest China. Agricultural Water Management, 2012, 104: 193–202
23. Turner N C. Techniques and experimental approaches for the measurement of plant water status. Plant and Soil, 1981, 58(1–3): 339–366
24. Mingo D M, Theobald J C, Bacon M A, Davies W J, Dodd I C. Biomass allocation in tomato (Lycopersicon esculentum) plants grown under partial rootzone drying: enhancement of root growth. Functional Plant Biology, 2004, 31(10): 971–978
25. Lo Bianco R, Talluto G, Farina V. Effects of partial rootzone drying and rootstock vigour on dry matter partitioning of apple trees (Malus
26. Williams L E. Determination of evapotranspiration and crop coefficients for a chardonnay vineyard located in a cool climate. *American Journal of Enology and Viticulture*, 2014, 65(2): 159–169

27. Du S, Kang S, Li F, Du T. Water use efficiency is improved by alternate partial root-zone irrigation of apple in arid northwest China. *Agricultural Water Management*, 2017, 179: 184–192

28. Stoll M, Loveys B, Dry P. Hormonal changes induced by partial rootzone drying of irrigated grapevine. *Journal of Experimental Botany*, 2000, 51(350): 1627–1634

29. Collins M J, Fuentes S, Barlow E W R. Partial rootzone drying and deficit irrigation increase stomatal sensitivity to vapour pressure deficit in anisohydric grapevines. *Functional Plant Biology*, 2010, 37(2): 128–138

30. Du T, Kang S, Yan B, Zhang J. Alternate furrow irrigation: A practical way to improve grape quality and water use efficiency in arid northwest China. *Journal of Integrative Agriculture*, 2013, 12 (3): 509–519

31. Consoli S, Stagno F, Roccuzzo G, Cirelli G L, Intrigliolo F. Sustainable management of limited water resources in a young orange orchard. *Agricultural Water Management*, 2014, 132: 60–68

32. Greenwood M S, Ward M H, Day M E, Adams S L, Bond B J. Age-related trends in red spruce foliar plasticity in relation to declining productivity. *Tree Physiology*, 2008, 28(2): 225–232

33. Du T, Kang S, Zhang J, Li F, Hu X. Yield and physiological responses of cotton to partial root-zone irrigation in the oasis field of northwest China. *Agricultural Water Management*, 2006, 84(1–2): 41–52

34. Mercier V, Bussi C, Lescourret F, Génard M. Effects of different irrigation regimes applied during the final stage of rapid growth on an early maturing peach cultivar. *Irrigation Science*, 2009, 27(4): 297–306

35. Jiang J, Huo Z, Feng S, Zhang C. Effect of irrigation amount and water salinity on water consumption and water productivity of spring wheat in Northwest China. *Field Crops Research*, 2012, 137: 78–88

36. Ji X, Kang E, Chen R, Zhao W, Zhang Z, Jin B. A mathematical model for simulating water balances in cropped sandy soil with conventional flood irrigation applied. *Agricultural Water Management*, 2007, 87(3): 337–346

37. Puerto P, Domingo R, Torres R, Pérez-Pastor A, García-Riquelme M. Remote management of deficit irrigation in almond trees based on maximum daily trunk shrinkage. Water relations and yield. *Agricultural Water Management*, 2013, 126: 33–45