RESEARCH PAPER

Total soil water content accounts for augmented ABA leaf concentration and stomatal regulation of split-rooted apple trees during heterogeneous soil drying

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Abstract

A split-rooted containerized system was developed by approach grafting two, 1-year-old apple (Malus × domestica Borkh. cv ‘Gala’) trees to investigate the effect of soil moisture heterogeneity and total soil moisture content (θv) on tree water relations, gas exchange, and leaf abscisic acid (ABA) concentration [ABAleaf]. Four irrigation treatments comprising a 2 × 2 factorial experiment of irrigation volume and placement were imposed over a 30-day period: control (C) [>100% of crop evapotranspiration (ETc)], applied to both containers; PRD100 (>100% ETc) applied to one container only; and two treatments receiving 50% ETc, applied to either one (PRD50) or both containers (DI50). Irrigation between PRD (partial rootzone drying) root compartments was alternated when θv reached ~35% of field capacity. Maximum daily sap flow of the irrigated roots of PRD100 exceeded that of C roots throughout the experimental period. Pre-dawn water potential (Ψpd) was similar between C and PRD100; however, daily water use and mid-day gas exchange of PRD100 was 30% lower. Slightly higher [ABAleaf] was observed in PRD100, but the effect was not significant and could not explain the observed reductions in leaf gas exchange. Both 50% ETc treatments had similar, but lower θv, Ψpd, and gas exchange, and higher [ABAleaf] than C and PRD100. Regardless of treatment, the container having the lower θv of a split-rooted system correlated poorly with [ABAleaf], but when θv of both containers or θs of the container possessing the higher soil moisture was used, the relationship markedly improved. These results imply that apple canopy gas exchange and [ABAleaf] are responsive to the total soil water environment.

Key words: Chemical signalling, deficit irrigation, Malus × domestica, partial rootzone drying, PRD, water use efficiency.

Introduction

There is evidence that roots produce chemical signals during soil drying which modify growth of the shoots prior to detectable changes in leaf water status (see reviews by Davies and Zhang, 1991; Sauter et al., 2001; Hartung et al., 2002; Dodd, 2003). Partial stomatal closure has been closely associated with an increase of foliar abscisic acid concentration [ABAleaf] during episodes of soil drying (Loveys, 1984). Direct evidence that root synthesis of ABA increases with declining soil moisture...
exists for several species (Davies and Zhang, 1989; Zhang et al., 1987). That root-derived ABA travels in the xylem to elicit stomatal effects has also been documented (Zhang and Davies, 1991); though the response varies with different species (Loveys et al., 1987).

Experimental drying of one half of maize (Zea mays L.) root systems provided early indications that non-hydraulic signals were responsible for stomatal regulation of split-rooted plants (i.e. exposure of roots to heterogeneous soil drying) within 2 d of partial root drying (Blackman and Davies, 1985); though partial stomatal closure was not attributed to [ABAleaf]. Elevated [ABA] in both epidermis and roots from drying soil of split-rooted Commelina communis L. plants occurred following 3 d of partial soil drying (Zhang et al., 1987). In an elegant study, Gowing et al. (1990) observed an unidentified root-sourced signal that reduced growth and transpiration of half-dried apple plants; these physiological effects disappeared when roots inhabiting dry containers were removed. Control of vegetative vigour was also observed when drying half of split-rooted peach (Prunus persica L.) (Tan and Buttery, 1982) and grapevine (Vitis vinifera) (Dry et al., 1996, 2000a, b). The latter investigations formed the framework of an agricultural irrigation strategy termed partial rootzone drying (PRD). In PRD, deficit irrigation is imposed by irrigating only a fraction of the rootzone per series of irrigation events. Stomata are regulated via chemical signals that preclude, or more probably, interact with hydraulic signals (Comstock, 2002) derived from the portion of roots inhabiting the drying soil. Irrigation is typically alternated between dry and wet rootzones in an effort to maintain a consistent signal. Early PRD investigations (Dry et al., 1996, 2000a, b) did not compare PRD with equally water-limited treatments where water was uniformly distributed to the entire rootzone. Subsequent experiments have been unable to relate the agronomic performance of divergent taxa to irrigation placement when comparing PRD and deficit irrigation (DI) using apple (Leib et al., 2006), common bean (Phaseolus vulgaris L.) (Wakrim et al., 2005), potato (Solanum tuberosum L.) (Liu et al., 2006), grapevines (Gu et al., 2004; Rodrigues et al., 2008), and tomato (Solanum lycopersicum Mill.) (Zegbe-Dominguez et al., 2003). A synopsis of the literature showed that yield ratios (PRD to DI) typically exceeded 1 for experiments performed on perennial horticulture crops, although the ratio was not significant for non-containerized studies (Dodd, 2009).

Stomata of apple seedlings responded rapidly to exogenous ABA under non-limiting growing conditions (Bingham, 1972). Further, a 20-fold increase in mature leaf [ABA] occurred as the water potential (Ψw) of water-stressed, potted apple trees declined from −0.4MPa to −2.6MPa (Bingham, 1972). ABA levels in apple leaves increased linearly with decreasing turgor potential following a 4 d water stress treatment (Davies and Lakso, 1978). Yet there is disparity between results of highly controlled apple split-root studies (Gowing et al., 1990) (demonstrating the capacity for apple to produce, and respond to chemical signals, but without directly measuring specific signals such as ABA), and field studies (TCE and HWC, unpublished; Leib et al., 2006), which have not observed effects of PRD on reproductive or vegetative growth relative to other DI regimes. It is possible that the signal:noise ratio associated with field conditions (i.e. high variability of the soil–plant–atmosphere continuum) is too great for consistent signal generation and action. Further, stomata of field-grown crops (specifically those with rough, discontinuous canopies) can be more sensitive to high vapour pressure deficit (VPD) (Pérez-Pérez et al., 2012) and plant water status (Rodrigues et al., 2008) than soil water availability.

In 2003, a unique system was developed to evaluate PRD by connecting two containerized apple trees via an approach graft. The split-root system (two root zones: one canopy) offered the potential to observe the proportion of sap flow and soil moisture of separate root zones of a split-rooted unit relative to canopy gas exchange, water relations, and [ABAleaf] in a factorial design with two levels of irrigation volume and two levels of irrigation placement. Dodd (2007) developed a novel two root—one shoot system using grafted tomato plants which was later applied to sunflower (Dodd et al., 2008a) to measure the relative contribution of individual roots to total plant sap flow and leaf xylem ABA.

The present study was designed to test the responsiveness of a scaled-up experimental unit (well-developed, 2-year-old apple trees with roots split between two 30 litre containers) to PRD. Approach grafting provided the opportunity to fix the volume of soil for root exploration, and more precisely control the soil moisture content of the separate containers. Furthermore, split-rooted plants enabled measurement of sap flow from both rootzones and the canopy. The hypothesis was tested that differences in soil moisture between individual pots of split-rooted apple trees and among treatments would account for differences in canopy gas exchange, and that PRD would augment apple [ABAcanopy]. Additionally, there was a technical objective of determining whether miniature sap flow sensors inserted into components of split-rooted apple trees could estimate whole-tree water use and characterize the relative root activity of split-rooted units during partial soil drying.

Materials and methods

One-year-old ‘Gale Gala’ apple trees grafted onto ‘Malling 7’ (‘M.7’) rootstocks were potted into 30 litre containers in a retractable-roof greenhouse. Thirty split-rooted units were formed by approach grafting two trees ~120cm above their scion–rootstock graft unions in late June of 2003. All split-rooted systems were allowed to callus and grow for the remainder of the year. Following bud-break in spring of 2004, one canopy was removed above the approach graft. Trees were fully watered until the beginning of the experimental period. Twenty similar units were randomly assigned treatments in a complete randomized design comprising 4 irrigation treatments each with 5 replications: (i) control (C), both containers irrigated once daily with >100% of their daily crop evapotranspiration (ETc; see below); (ii) PRD100, one container irrigated once daily with >100% of daily ETc, the other receiving no irrigation; (iii) DI50, both containers irrigated once daily with 50% of daily ETc, distributed evenly between the two containers; and (iv) PRD50, one container irrigated once daily with 50% of daily ETc, the other receiving no irrigation. Daily irrigation of all treatments occurred in the evening. Irrigation of PRD treatments was alternated between wet and dry root compartments on day of year (DOY) 208, 215, and 223 when soil moisture extraction was observed to have levelled off in the dry compartment (~35% of field capacity (FC)). Unless otherwise noted, trees were watered by hand once per day (at dusk) using watering cans filled with the exact percentage of their daily ETc. In the case of C and PRD100, all replications received an additional 20% ETc to
account for losses due to drainage. Semi-transparent, polyethylene covers were fitted across the surface area of all containers following irrigation to eliminate the evaporative component of ET. The experimental period was from 19 July to 18 August, 2004 (DOY 200–230). Following completion of two PRD drying cycles, deficit treatments were terminated and full irrigation was provided, but the distribution of water was unchanged (i.e. PRD50 became PRD100, and DI50 became C). The switch to full irrigation was intended to evaluate the recovery time of gas exchange and water use of the former deficit treatments.

The medium was a native soil:organic mixture (~1:1 v/v). The organic constituents, and their relative proportions within the organic fraction, had not been experimentally determined. The experimentally derived bulk density (Bd) of the medium (0.75 g cm\(^{-3}\)) and known BdS of various organic components were used to calibrate \(\theta_v\) measurement by time-domain reflectometry (TDR) (Tektronix Model 1502C, Beaverton, OR, USA), based on the equations of Topp \(\text{et al.}\) (1980). Stainless steel waveguides, 6 mm in diameter, 300 mm in length, were inserted into each container of the split-rooted units for all replications. Waveguides captured the entire depth of the container, spanning from the bottom of containers, and protruding ~2.5 cm from the medium surface to enable measurements. Throughout the first 12 d of the experimental period, \(\theta_v\) was measured in the morning, after drainage from the preceding night, and again in the evening, prior to irrigation. Daily water use was calculated as the difference between the morning and evening measurements. Thereafter, water content was measured once daily, in the morning. For the first 7 d of the experiment, gravimetric measurements were made using a transportable 4 m high wooden tripod utilizing three S-type load units were determined from measurements of sap flow using the Tmax method (Cohen \(\text{et al.}\), 1990). The water fraction collected during separatory phases containing organic constituents, and their relative proportions within the organic fraction, were inserted into each root shank (below the approach graft union) and in the stem above the approach graft union. Sap velocity was measured at two radial depths (5 mm and 10 mm) in the stem and one depth (5 mm) in the root shanks. A 0.7 s heat pulse was applied every 30 min and data were collected via a data logger (Campbell Scientific, Logan, UT, USA). Heat pulse velocity was converted to sap flow based on the trunk cross-sectional area (TCA) at the sites of insertion. Correction factors for wounding were derived according to Green \(\text{et al.}\) (2003).

Gas exchange \(\left[\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}\right]\); \(g_s\), stomatal conductance (mmol m\(^{-2}\) s\(^{-1}\)); \(E\), transpiration (mmol m\(^{-2}\) s\(^{-1}\)); WUE\(_{\text{hve}}\), water use efficiency) was quantified using a PP systems Ciras-2 gas analyser (PP systems, Amherst, MA, USA) on three replications per treatment (two leaves per replication). Measurements were taken on the first fully mature sunlit leaves of extension shoots, between 12:00 h and 14:00 h on days with fairly similar climatic conditions. In addition, hourly measurements were made on several dates to capture diurnal changes in gas exchange. All measurements were made under natural saturating photosynthetically active radiation (PAR) for apple leaves (>1000 \(\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}\)), unless otherwise stated.

Pre-dawn leaf water potential (\(\Psi_{pd}\)) was determined on three replications (two leaves per replication) using a pressure chamber (model 600, PMS, Corvallis, OR, USA) according to the Scholander method (Scholander \(\text{et al.}\), 1965).

Leaf area (LA) was measured at the conclusion of the experimental period on a 10% sample (w/w) per tree with a calibrated leaf area meter (Licor LA 3100, Lincoln, NE, USA).

Whole leaves were collected for ABA analysis from three replications (two leaves per replication), immediately dipped in liquid N, and held at ~80 °C for several weeks prior to lyophilization. Procedures for ABA extraction and purification of apple tissue were previously developed for enzyme-linked immunosorbent assay (ELISA) (Soejima \(\text{et al.}\), 1990). The water fraction collected during separatory phases containing conjugated ABA was not examined.

Quantification of 2-cis-(S)-ABA was by a competitive ELISA (Agdia, Elkhart, IN, USA), using a spectrophotometer (Spectramax 384 Plus, Molecular Devices Corp., Sunnyvale, CA, USA) equipped with a 96-well microtitre plate reader and temperature-controlled incubation.
chamber. Procedures were outlined by Agdia Inc. (Elkhart, IN, USA). Internal standards [2-cis-(S)-ABA; Sigma-Aldrich, St. Louis, MO, USA] were added to sample tissue prior to the extraction protocol for calculation of recovery rates. In all samples, ABA recovery rates were between 75% and 85%. Standard curves were prepared with each plate and linearized using log logit transformation. Samples always fell within the linear range of the standard curves. Samples were excluded from further interpretation if the coefficient of variability for duplicate values was >0.10.

Statistical analyses were performed using the SAS system software (SAS Institute, Cary, NC, USA). Treatment means were compared using analysis of variance (ANOVA; PROC GLM) and significance was tested at $P \leq 0.05$. Mean separation was determined by Fisher’s Protected LSD. PROC REG was used for regression analyses. In the case of the relationship between relative TCA and sap flow of individual root shanks of a split-rooted unit, percentages were arcsine transformed prior to analysis.

Results

To determine whether TDR accurately estimated $\theta_v$, data were regressed against gravimetric soil moisture content ($\theta_w$). The relationship between $\theta_w$ and $\theta_v$ was highly significant ($P < 0.0001$) [$\theta_v(L) = 1.028 \theta_w, (kg), r^2 = 0.85, (n = 167)$]. There was also generally good agreement between $T_{max}$ and $\theta_v$; data fit the 1:1 relationship (Fig. 1), though variability existed in the relationship ($r^2 = 0.63$), especially at higher flows (i.e., Controls). Variance between the two measured parameters is likely attributed to several assumptions inherent in each of the techniques. The $\theta_v$ of the irrigated root compartment of PRD100 plants was comparable with $\theta_v$ of C containers from DOY 200 to DOY 214, while the PRD100 non-irrigated container was progressively depleted to a minimum total water content of 3.5 litres on DOY 207, following 8 d of drying (Fig. 2A). PRD100 irrigation was then alternated between sides on DOY 208. Subsequent switching of irrigation between wet and dry compartments was conducted on DOY 215 and 223 when ~3.5 litres of total soil water remained in the ‘dry’ profile, which constituted drying periods of 9 d and 7 d, respectively. The irrigated compartment of the PRD100 treatment only recovered to 70% of C $\theta_v$ between the second and third switch (DOY 215–222). The PRD50 ‘dry’ compartment levelled off at 3.5 litres on DOY 207 (similar to the PRD100 ‘dry’ compartment on that date). The irrigated compartment of PRD50, however, steadily declined over the first deficit cycle, reaching 35% of C $\theta_v$ on DOY 207. On DOY 215, PRD50 was changed to PRD100, and the irrigated compartment reached and sustained $\theta_v$ of C by DOY 219. The average $\theta_v$ of both containers of the PRD50 treatment remained ~15% higher than that of DI50 throughout the first drying cycle, but attained similar levels on DOY 214. The mean $\theta_v$ of DI50 declined to 3.6 litres on DOY 214, after which it returned to a C treatment (Fig. 2B). The ensuing daily application of >100% ETc to DI50 required an additional 7 d for $\theta_v$ to recover to C levels. Total daily water use was reduced for PRD100 relative to C despite receiving a similar volume of water, but differences in total daily water use between PRD50 and DI50 were not observed (Fig. 2C).

Prior to the start of the experiment, $\theta_v$ in all containers was brought up to pot capacity. A highly significant, positive relationship was observed between relative sap flow of roots comprising individual split-rooted units and their TCA

Fig. 2. The effects of irrigation treatments on average soil water content of split-rooted, 2-year-old ‘Gale Gala’ apple trees; C and PRD100 (A), and DI50 and PRD50 (B). Total daily water use of C, PRD100, PRD50, and DI50 calculated from the difference between morning and evening time-domain reflectometry measurements on successive days from DOY 200 to 211 (C). Data are means of five replications. Mean separation by Fisher’s Protected LSD test at $P < 0.05$. The inset in C provides the daily irrigation volume for individual treatments throughout the entire experimental period. Vertical dashed lines signify switches in
Effects of soil water content on gas exchange and foliar ABA of split-root apple trees

The dependency of sap flow on TCA indicated that the approach graft union did not markedly alter the hydraulic properties of the split-rooted units, irrespective of the origin of the root system (i.e. whether the sap flow was measured in the root of the tree whose canopy had been removed above the approach graft, or the root of the intact tree). Further, the sum of sap flow of the two root systems below the approach graft unions comprised 100.2% (SD 17.8%) of the sap flow measured above the approach graft union (mean of the six split-rooted units fitted with heat pulse sensors). Individual root sap flow of split-rooted C units maintained consistent levels throughout the entire experimental period (Fig. 3A). Root activity of individual compartments of all PRD split-rooted replications responded consistently and rapidly to wetting events by increasing sap flow, and daily water use, from the irrigated side, while reducing sap flow from the drying side (Fig. 3B, 3C). Throughout this bi-phasic process, with the exception of the day immediately succeeding the irrigation switch between PRD containers, total daily water use of PRD100 trees remained fairly consistent during the experimental period (Fig. 2A, 2C).

The Ψpd of PRD100 was not significantly different from that of C throughout the entire experimental period, although PRD100 values were slightly lower than those of C on several occasions (Fig. 4A). Both deficit treatments had lower Ψpd than C and PRD100 beginning on the fifth day into the drying cycle (DOY 204) and, with the exception of DOY 209, Ψpd of PRD50 and DI50 units was similar (Fig. 4A). Both treatments recovered to C and PRD100 levels following DOY 214, when the deficit period was terminated.

Mid-day gs, A, and WUE of PRD100, PRD50, and DI50 trees were progressively reduced during the first 10 d of the experimental period, relative to C (Fig. 4B–D). The percentage reduction of gs relative to C during the 15 d deficit period was 30, 45, and 54% for the PRD100, PRD50, and DI50, respectively. Similar reductions were observed for E and A (Fig. 4C). Gas exchange of PRD50 recovered to PRD100 levels within 1 week from its change to a PRD100 regime; however, DI50 never reached C values for gs or A after receiving full irrigation, despite maintaining an equivalent soil moisture status to that of C.

Examples of the diurnal patterns of gas exchange are presented for DOY 203 and DOY 208 (4 d and 9 d into the experimental period) (Fig. 5A–F). Irrespective of soil moisture status (Fig. 2), all treatments experienced a diurnal fluctuation in gas exchange, though the magnitude varied with treatment. On DOY 203, gs of both PRD50 and DI50 was significantly different from that of C by mid-morning, and approached significance for solar noon (P=0.07) and late afternoon (P=0.06) (Fig. 5A). Although DI50 values were lower than PRD50, the differences were not significant. The average mid-day E for PRD100, PRD50, and DI50 expressed as a percentage of C was 79, 68, and 55%, respectively. Substantial soil water deficits had accrued by DOY 208 (Fig. 2), resulting in marked and significant reductions of gs for deficit treatments (Fig. 5B). Average daily single-leaf transpiration of PRD100 was ~87% of that of C, while those of PRD50 and DI50 were reduced to 33% and 37% of C, respectively. Whole-plant transpiration was similarly reduced as determined by TDR (86, 42, and 49% of C for PRD100, PRD50, and DI50 trees, respectively; Fig. 2C), or for trees instrumented with Tmax (PRD100 and PRD50 were 77% and 42% of C, respectively). On both dates, diurnal patterns of $\dot{A}$ were similar to those of $\dot{g}_s$, though significant differences
among treatments were not detected at $P < 0.05$ (Fig. 5C, 5D). Cloud cover at solar noon on DOY 208 markedly reduced the PAR (from 1600 µmol m$^{-2}$ s$^{-1}$ at 10:00 h to 200 µmol m$^{-2}$ s$^{-1}$ at 12:00 h) and thus limited $A$ of C and PRD100 treatments (Fig. 5D). Because of the strong linear relationship between $A$ and $g_s$ ($r^2=0.78$, $P=0.0001$; Fig. 5G), WUE was not improved by deficit irrigation treatments (Fig. 5E, 5F).

Bulk [ABA$_{leaf}$] (ng g$^{-1}$ dw) for PRD100 and C did not significantly differ throughout the experimental period, although PRD100 generally had slightly higher [ABA$_{leaf}$] than C (Table 1). In contrast, [ABA$_{leaf}$] of deficit treatments increased sharply by DOY 203 and remained significantly elevated over C until DOY 221, which was 1 week following the return of these treatments to their >100% ET$_c$ counterparts (Table 1). On DOY 203 and 208 [ABA$_{leaf}$] of DI50 was markedly higher than that of PRD50, though not significantly. Low treatment sampling (three replications; $n=2$), high variability associated with [ABA$_{leaf}$] content, concomitant with observed heterogeneity within treatment $\theta_v$ limited the statistical separation between treatments. On DOY 211, 3 d after PRD irrigation was alternated

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**Table 1.** The effect of irrigation treatment on leaf abscisic acid concentration (ng g$^{-1}$ dw) of split-rooted, 2-year-old containerized ‘Gale Gala’ apple trees on selected dates [day of year (DOY)]. DOY 200 was day 1 of the experiment. Irrigation was alternated between the wet and dry containers of PRD treatments on the evenings of DOY 208, 215, and 223. On DOY 215, PRD50 and DI50 were changed to PRD100 and Control treatments, respectively.

| Treatment | DOY 200 | DOY 203 | DOY 208 | DOY 211 | DOY 216 | DOY 221 |
|-----------|---------|---------|---------|---------|---------|---------|
| Control   | 97      | 107 b   | 253 b   | 73 b    | 58      | 106     |
| PRD100    | 110 (114)| 157 b (147)| 296 b (117)| 88 b (120)| 76 (132)| 92 (87) |
| PRD50     | 107 (110)| 261 a,b (244)| 438 a,b (173)| 221 a (302)| 100 (173)| 93 (87) |
| DI50      | 108 (111)| 438 a (409)| 774 a (306)| 139 b (190)| 82 (141)| 93 (87) |

Data are means of three replications ($n=2$).
Means within columns for each date followed by different letters are significantly different at $P < 0.05$.
Values in parentheses are treatment ABA as a percentage of control.

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Fig. 4. The effects of irrigation treatments on 2-year-old, split-root containerized ‘Gale Gala’ apple leaf pre-dawn water potential (A), stomatal conductance (B), net assimilation (C), and water use efficiency (D). Data are expressed as a percentage of control (C). On DOY 215, PRD50 and DI50 were changed to PRD100 and Control treatments, respectively. Vertical dashed lines signify switches in irrigation between PRD ‘wet’ and ‘dry’ compartments. Asterisks on the bottom represent significance at $P < 0.05$. Each point is the mean of three replications ($n=2$).
between wet and dry compartments, PRD50 had significantly higher [ABA_{leaf}] than its deficit counterpart (Table 1). The relative effects of soil drying can be observed when the data are expressed as a percentage of C to account for fluctuations in the absolute [ABA_{leaf}] of C trees (Table 1). [ABA_{leaf}] increased with decreasing soil moisture through the first drying cycle in

**Fig. 5.** The effects of irrigation treatments on single-leaf gas exchange of split-rooted, 2-year-old containerized ‘Gale Gala’ apple trees, on DOY 203 (A, C, E) and DOY 208 (B, D, F), 2004. Stomatal conductance (A and B), net assimilation (C and D), and WUE (E and F). Asterisks on the bottom represent significance at P < 0.05. Each point is the mean of three replications (n=2). (G) The relationship between photosynthesis and stomatal conductance recorded at solar noon. Data were combined for both dates due to non-significant differences between slopes for individual dates. The regression line was fitted through the data: y=0.032x+0.286, (r^2=0.78, P < 0.0001).
all treatments relative to C (Table 1, Fig 2A, 2B), irrespective of irrigation placement (i.e. applied to one container or two).

[ABAleaf] was significantly, negatively correlated with θ, of the wet compartment during the first 8 d of the drying cycle (r²=0.61, P < 0.0001) (Fig. 6A). A similar relationship was observed between total θ, (sum of both containers) and [ABAleaf] (r²=0.6, P < 0.0001), but the relationship was markedly weakened when θ, of the dryer container was regressed against [ABAleaf] (r²=0.39, P < 0.0001). [ABAleaf] versus θ, of the wet compartment remained highly significant when the entire data set was analysed (P < 0.0005); however, the variability was noticeably higher (r²=0.16, Fig. 6B), as was the case when the relationships between [ABAleaf] and either total θ, or minimum container θ, were analysed. Stomatal conductance and [ABAleaf] were negatively correlated (P < 0.0001) following 7 d of soil drying (Fig. 6C), but the relationship was substantially weakened when all data points were analysed (Fig. 6D).

**Discussion**

For the 30 d experimental period, apple trees receiving >100% ETc to one container of a PRD100, split-rooted system, while the other was allowed to dry, exhibited a 30% and 28% reduction in mid-day single-leaf gas exchange (Fig. 4B, 4C), and whole plant transpiration (determined by sap flow), respectively, relative to well-watered C plants. Drainage from the irrigated compartment of the PRD100 containers was not measured, though the net increase of soil moisture in the irrigated container following irrigation and drainage was roughly equivalent to the previous day’s water use (determined via TDR measurements).

Reduced gas exchange could not be attributed to a difference in [ABAleaf] between PRD100 and C. Although [ABAleaf] of PRD100 increased, albeit non-significantly, to 147% of C levels on DOY 203 (Table 1), it was only slightly higher than C on all but the last sampling date, when it was in fact lower than C. Because prevailing xylem sap [ABA] has been more sensitively related to
Mechanisms were not investigated in the present study. Therefore plausible that a minimal shift in one or several of these \( \Psi \)., 2006), and declining (Tardieu and Davies, 1992; Soar et al., 1998; Sobeih et al., 2012), high VPD (Tardieu and Davies, 1992; Soar et al., 2006), and declining \( \Psi \) (Behl and Hartung, 1984; Tardieu and Davies, 1993). It is therefore plausible that a minimal shift in one or several of these factors may have amplified the PRD100 signal; however, these mechanisms were not investigated in the present study.

That total \( \theta \), of both containers, or of the container possessing the higher \( \theta \), was better correlated with [ABA] \(_{leaf}\) than \( \theta \), of the non-irrigated container of a PRD unit, or the container with the lower \( \theta \), for C or DI50 units, indicates that drying roots in the ‘wet’ compartment probably contributed additional ABA to the leaves, or modified signal strength. Liu et al. (2008) observed a strong relationship between average xylem [ABA] of the wet and dry roots and xylem [ABA] of potato plants. Measured differences in [ABA] \(_{leaf}\) between PRD100 and PRD50, and nearly identical rates of sap flow and \( \theta \), depletion of dry containers prior to re-wetting of these treatments (Figs 2, 3B, C), suggest that [ABA] \(_{leaf}\) depends strongly on the \( \theta \), of the wet container, as modelled by Dodd et al. (2008a) and observed experimentally (Romero et al., 2012). If [ABA] \(_{leaf}\) production and transport were wholly dependent upon the status of the dry roots, PRD100 and PRD50 would have had similar [ABA] \(_{leaf}\). Additionally, a plausible explanation for why [ABA] \(_{leaf}\) was highest in DI treatments early in the experimental period (Table 1, Fig. 2) is that more roots were in contact with an ‘optimal’ range of \( \theta \), for both root ABA synthesis and its transport to the shoot, as hypothesized by Dodd et al. (2008b). The higher [ABA] \(_{leaf}\) of PRD50 on DOY 211, following re-irrigation of drying roots on DOY 208, might have derived from liberated pools of ABA from previously drying roots (Dodd et al., 2006); however, this was not observed for the DI50 treatment when returned to full irrigation on DOY 215, or PRD100 following switches (Table 1, Fig. 3B). The frequency of the sampling interval used was too long to identify a threshold \( \theta \), for the irrigated root system of a PRD unit to optimize [ABA] \(_{leaf}\), but the data generally support modelled predictions of Dodd et al. (2008a), and underscore the need to account for \( \theta \), of both root systems in order to sustain [ABA] \(_{leaf}\) when soil moisture heterogeneity exists (Wang et al., 2012).

Similar reductions in gas exchange for PRD50 and DI50, however, were quite different. On DOY 203, under conditions of mild stress after only 3.5 d of pot drying, [ABA] \(_{leaf}\) of PRD50 and DI50 was 2.6- and 4.4-fold higher than that of C, and \( g_s \) was reduced by 32% and 61% of C, respectively. Concomitantly, \( \Psi_g \) of both treatments was sustained at C levels. In contrast, on DOY 208, the afternoon preceding the first switch for PRD regimes, \( \Psi_g \) of both deficit treatments was significantly lower than that of C, and \( g_s \) was reduced by ~74% (Fig. 4A, 4B), indicating severe stress, despite increased levels of endogenous [ABA] \(_{leaf}\). The marked increase observed in [ABA] \(_{leaf}\) for both of these treatments, and particularly for DI50, may have been the result of leaf ABA synthesis. Soar et al. (2004) have documented synthesis of ABA in grape leaves when relative water content fell to 85%. Stoll et al. (2000) observed a 5-fold increase in [ABA] \(_{leaf}\) of DI-treated grapevines compared with PRD, and this difference was related to the reduced leaf water status of the DI compared with the PRD treatment. Others, however, have shown that leaf synthesis of ABA does not occur until turgor approaches zero (Pierce and Raschke, 1980). The lower \( \Psi_g \) recorded for PRD50 plants is at odds with tight stomatal regulation of leaf water status, although, in our case, \( \Psi_g \) reflected the energy status of the soil, assuming equilibrium between the plant and the soil was reached. Further, apple leaves remained visually turgid at mid-day on all measurement dates, irrespective of irrigation treatment.

In two separate field studies with apple in the temperate climate of New Zealand and the semi-arid climate of Washington State, USA, it has been shown that irrigation volumes of 50% relative to a control were insufficient to maintain a wet profile with PRD (Leib et al., 2006), as was also confirmed in the present container study (Fig. 2B). In fact, the cumulative development of soil water deficit in the wet profile of PRD treatments irrigated at 0.5 ET \(_c \) is evident in studies with grapevine (Santos et al., 2005), tomato (Zegbe-Dominguez et al., 2003; Kirda et al., 2004; Zegbe et al., 2006), hot pepper (Capsicum annum L. ‘Ancho St. Luis’) (Dorji
et al., 2005), potato (Liu et al., 2006), maize (Kirda et al., 2005), common bean (Wakrim et al., 2005), and olive (Wahbi et al., 2005). Subsequently, in most of the afore-mentioned studies, leaf Ψ of PRD plants was reduced relative to the well-watered control. In the present study, 50% ETc applied via PRD had an equally deleterious effect to DI50, because progressive drying of the ‘wet’ soil profile led to similar degrees of plant water stress (Figs 4, 5). In contrast, studies which maintained soil moisture near FC in the irrigated side of PRD (such as in PRD100) did not detect a significant decline in plant water potential, but observed a significant reduction in g∗ (Dry and Loveys, 1999; Toit et al., 2003; Mingo et al., 2004; Sobieh et al., 2004).

The difficulty of reconciling a chemical signal to physiological effects under controlled environments (cf. Fig. 6C, 6D) underscores the challenges associated with experimental and commercial application of PRD in field situations; slow drying of heavy soils, heterogeneity of physical and chemical properties of soil and moisture availability within a profile, low root length densities (e.g. perennial crops), atmospheric factors, and, in apple, strong active osmotic regulation (Lakso, 1979) do not favour agricultural management of such a highly transient, and rapid signal. Non-stressed apple WUE is quite high (Lakso, 2003) and, significant stomatal closure of apple leaves, whether due to hydraulic or chemical signals, will adversely affect carbon supply (Fig. 5G), and ultimately dry matter accumulation in fruit. One tenet of PRD is the increase in WUE when water supply is limited, though in the climate studied here, intrinsic WUE of apple was not increased for any deficit treatments when gas exchange was reduced (Fig. 5), contrary to previous studies of PRD-treated perennial crops (Egea et al., 2011; Romero et al., 2012). While intrinsic WUE is determined from point measurements, the lack of a consistently elevated ABA signal (Table 1), similar water use (Fig 2C), and non-significant differences in canopy leaf area in PRD plants compared with their equally watered counterparts suggest that long-term WUE would probably behave similarly. However, it should be noted that in the climate in the present experiments apple shoot growth is largely complete by mid to late July (i.e. coinciding with the beginning of the experimental period in the current study). Therefore, in other climates, or during periods of rapid vegetative growth, reductions in gas exchange similar to those that were observed here would probably have marked impacts on leaf area, and subsequently after long-term WUE. PRD-treated lemon [Citrus limon (L.) Burm. fil.] trees had increased long-term WUE compared with DI, despite both treatments possessing similar intrinsic WUE (Pérez-Pérez et al., 2012).

Split-rooted, well-developed apple trees were capable of producing chemical signals during soil drying when irrigation was limited to 50% ETc, irrespective of water placement (e.g. DI or PRD), but differences in mid-day stomatal regulation between the two treatments were not significant (Fig. 4) (Wang et al., 2011). However, when provided with >100% ETc, PRD100 [ABAleaf] was not significantly elevated above C levels to link it unequivocally to the lower daily water use and gas exchange of PRD100 compared with C (Figs 2C, 4 B–D). The fact that PRD50 had higher [ABAleaf] than PRD100 despite possessing equivalent dry container θ, indicates that the soil moisture status of the irrigated rootzone of PRD-treated plants significantly modulates canopy gas exchange (as previously modelled; Dodd et al., 2008a, b; and observed experimentally; Romero et al., 2012). The relatively low soil moisture availability of PRD50 wet and dry root compartments did not result in a consistent, optimal ABA supply (Table 1), or maintain high plant water relations (Figs 4, 5) (Wang et al., 2012). Further investigations are required to define the threshold soil moisture status and its relationship with ABA signalling of the drying root system of PRD apple for alternating irrigation between wet and dry containers. In the present experiment, soil water depletion of the dry root system of PRD100 may have been too severe prior to the switch in irrigation on DOY 208 (Fig. 2A) to elicit augmented [ABAleaf] (Table 1). Insignificant changes in PRD100 gas exchange immediately succeeding irrigation switches (Fig. 4B, 4C) and only slight, non-significant differences in [ABAleaf] between PRD100 and C 3 d following the first switch (DOY 211) and the day immediately succeeding the second switch (DOY 216) (Table 1), do not concur with previously published results showing liberated ABA pools following re-watering of dry PRD roots (Dodd et al., 2006). In general, the data indicate that apple water use and [ABAleaf] are associated with the overall soil moisture environment. Future characterization of [ABA] immediately following irrigation alternation and its dependency on a threshold sap flow from roots in drying soil (Dodd et al., 2008a, b) would elucidate the physiological potential, and inform both the experimental and agronomic utility of PRD.

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