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Growth, fruit yield and quality of 'Golden Delicious' apple trees under fixed partial rootzone drying

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Abstract

We investigated the vegetative and productive responses of 'Golden Delicious' apple (*Malus domestica* Borkh.) trees to fixed partial rootzone drying under the dry climate of central Sicily. Soil water content (SWC), stomatal conductance, yield, fruit quality, fruit growth, and vegetative growth of conventionally irrigated trees (CI), where drip emitters on both sides of each tree were left open, were compared to that of fixed partial rootzone drying (FPRD) trees where only one side of the rootzone was irrigated for the entire season thus receiving 50% of the CI irrigation water. The irrigation season started on 31 July and ended on 13 September, 2004. Wet and dry rootzone sides showed significantly different SWC from 16 August until 14 September, whereas stomatal conductance of CI and FPRD trees differed significantly starting on 24 August. Relative growth rate of CI fruit was higher than that of FPRD fruit on 27 and 31 August, but fruit size was similar during the entire sampling period and at harvest. Trees of the two treatments had similar yields, number of fruits, crop load, fruit:leaf ratio, fruit quality, tree height, wood fresh and dry weight, canopy spread area, volume and density, shoot length and number, internode length, and leaf area. FPRD trees had higher yield efficiency, thinner shoots, lower leaf water content, higher canopy density and leaf dry weight and specific leaf weight than CI trees. Our observations suggest the extent of possible water savings without loss of yield and fruit quality using this partial rootzone drying strategy in 'Golden Delicious' apple orchards of central Sicily.

Key words: Canopy size, crop load, deficit irrigation, fruit growth, fruit quality, leaf area, shoot length, stomatal conductance, yield.

Introduction

Fruit production in semi-arid climates is subject to high evapotranspiration, increased soil salinity, and limited water availability. For these reasons, maximizing yields with minimal irrigation inputs, *i.e.*, increasing plant water use efficiency, becomes essential.

Plants growing under water deficit conditions can partly maintain cell turgor by closing stomata (Parker and Pallardy, 1985). Yet, stomatal closure for varying periods of time can impair CO_2 assimilation and may reduce the structural and energetic support for growth (Hsiao, 1973). This often leads to significant yield reductions especially in fruit crops. On the other hand, mild water deficit can induce partial stomatal closure which may result in improvements of water use efficiency due to the non-linear relationship between stomatal conductance and assimilation (Turner, 1997). Moderate water deficit may also alter resource allocation in favour of reproductive development (Yang *et al.*, 2000). Seeds and fruits are in fact, stronger growth sinks than shoot apices (Wardlaw, 1990) and under drought and limiting assimilation rates, vegetative growth is reduced more rapidly than reproductive growth (Higgs and Jones, 1991).

Regulated deficit irrigation (RDI) was developed to minimize irrigation inputs for fruit production in areas where water is a limiting resource. It consists of withholding water during certain periods to produce a moderate drought stress and to obtain beneficial consequences on fruit quality while limiting shoot growth. Results of RDI experiments have been promising in certain regions and for some fruit crops, such as peach (*Prunus persica* L.) (Chalmers *et al.*, 1981), pear (*Pyrus communis* L.) (Mitchell *et al.*, 1984; Mitchell *et al.*, 1989; Caspari *et al.*, 1994), French prune (*Prunus domestica* L.) (Lampinen *et al.*, 1995), and olive (*Olea europea* L.) (Goldhamer, 1997). In these species, vegetative and reproductive growth occur during different periods allowing for control of shoot growth without any decrease in fruit size or yields (Chalmers e*t al.*, 1981). On the other hand, apple (*Malus domestica* Borkh.) fruits and shoots grow concurrently (Forshey *et al.*, 1983) and water deficit usually reduces fruit size and yields irrespective of timing (Lötter *et al.*, 1985; Ebel *et al.*, 1993, 1995; Mpelasoka *et al.*, 2001; Caspari *et al.*, 2004b; Leib *et al.*, 2006).

Partial rootzone drying (PRD) is an irrigation technique that was recently developed in Australia for grapes (*Vitis vinifera* L.) (Dry *et al.*, 1995; Dry and Loveys, 1998). With PRD, only one half of the rootzone is irrigated whereas the other half is not. The physiological basis for PRD is that roots in drying soil produce abscisic acid (ABA) which is translocated to the shoots, indicating a developing soil-water deficit (Dry *et al.*, 1995). In leaves, ABA induces partial stomatal closure which reduces transpiration and may increase water use efficiency. At the shoot meristem, ABA may reduce shoot extension, but because the other half of the rootzone is kept well watered, the effect on plant water potential is minimal (Gowing *et al.*, 1990). Other metabolic and physiological processes associated to water stress are not affected during PRD (Dry *et al.*, 1995; Dry *et al.*, 2000). PRD relies on cyclical wetting and drying of parts of the rootzone in order to maintain root derived ABA signals (Zhang and Davies, 1987). Yet, fruit yield, stomatal conductance (g_s), and shoot growth of raspberries (***Rubus idaeus*** L.) was similar in alternated and fixed PRD where there was no switching of wet and dry sides (Grant *et al.*, 2004).

In studies conducted on 'Braeburn', 'Fuji', and 'Gala' apples (Caspari *et al.*, 2004 a, b; Einhorn and Caspari, 2004; Lombardini *et al.*, 2004), PRD should allow for a good final fruit size of apples and possibly for a reduction in shoot growth due to a lower number of nodes (rather than shorter internodes) along with a significant reduction in irrigation water. For this reason, PRD has a significant potential to become a beneficial irrigation strategy in those fruit crops where RDI has led to negative outcomes. Our objective was to examine the productive and vegetative responses of 'Golden Delicious' apple trees to fixed PRD in the semi-arid climate of central Sicily. We hypothesized that FPRD would not only save water but could also reduce vegetative growth without sacrificing 'Golden Delicious' fruit yield or quality.

Materials and methods

The study was conducted near Caltavuturo (37° 49' N and 850 m above sea level), Sicily, Italy. Trees were 42 uniform six-year-old 'Golden Delicious' apple trees grafted on MM 106 rootstock trained to a central leader. Trees were planted in single rows (north-south oriented) spaced at 4 m between rows and 1.5 m within the row and arranged in a randomized complete block design with three replicates of seven trees per irrigation treatment (described below). The soil type was a sandy clay loam with pH 7.3 and 18% active carbonates. Soil moisture content at field capacity was about 0.27 $m^3 m^{-3}$. Trees were drip irrigated using one dripper every 1.5 m and received conventional cultural care.

In July 2004, five of the seven trees (one tree at each end was left as buffer) per treatment-replicate combination (total 30 trees) were selected and labeled. For the conventional irrigation treatment (CI), all drip emitters on the line located between consecutive trees along the row were left open so that trees were receiving water on both north and south sides of the rootzone. Irrigation maintained soil water content above 80% of field capacity. For the FPRD, the drip emitter on one side of each of 15 trees was closed and the emitter on the other side was left open so that trees were receiving 50% of the CI irrigation water only on one side of the rootzone.

Wet and dry sides of the rootzone were not alternated because of the relatively short irrigation season of 44 days (typically the irrigation season in this area ranges from 60 to 75 days), the relatively constant soil water content (around 0.2 $m^3 m^{-3}$) in the dry side during the last two thirds of the irrigation season, and the significantly reduced stomatal conductance of FPRD trees for the entire second half of the irrigation season. Also, since previous trials with 33% season-long irrigation reductions using neighboring trees had led to significant fruit size and yield reductions, a treatment with 50% irrigation of CI distributed on both sides of the rootzone was not included.

Soil water content (SWC), g_s, and fruit growth were monitored twice a week from 3 August until 16 September. SWC was measured in each block on the wet and dry side of the FPRD treatment at the fixed soil depth of 40 cm by time domain reflectometry (Trase Systems-Soil Moisture Equipment Corp., Santa Barbara, CA, USA). SWC of CI treatment was assumed to be similar to the wet side of the FPRD treatment. Stomatal conductance was measured between 11:00 and 13:00 HR on two leaves, each located on one side (East and West) of the tree, with an AP4 Delta-T porometer (Delta-T Devices, Cambridge, UK). Mature, fully expanded, but non-senescent leaves on extension shoots were selected for g_s measurements. Fruit growth was monitored non-destructively on one fruit per tree. Each fruit was photographed against a white background and next to a reference tape with a digital camera, and fruit vertical cross-sectional area was determined after editing and calibration of the images. Climate data were obtained from an official weather station of the Sicilian Agro-Meteorological Information Service located nearby in the same farm. Vapor pressure deficit (VPD) was calculated from average daily temperature (T in °C) and relative humidity (RH in %).

Fruit were harvested on 22 September and total fruit weight and number per tree were determined in the field, and a sub-sample of 30 fruit per tree was taken to the laboratory for quality analysis. In the laboratory, each fruit was photographed (under identical light conditions provided by two 18-watt fluorescent lamps) and digital images were used to determine final fruit size (vertical cross-sectional area) and peel color. Peel color was determined by digital image analysis using an algorithm developed with MATLAB® software (The Mathworks Inc.) that converts images from RGB to CIE 1976 L*a*b format (by lookup tables), extracts the fruit from the image (removing the image background), and quantifies color characteristics as the weighed distance of each pixel in the image from a reference sample (best colored area interactively chosen from a well colored fruit). The output is an index ranging from 0 (green) to 1 (yellow). Subsequently, flesh firmness (with a manual pressure tester mounting a 8-mm tip, TR di Turoni & Co., Forlì, Italy), total soluble solids (with an Atago Palette PR-32 digital refractometer, Atago Co., Ltd., Tokyo, Japan), juice pH, titratable acidity (with a Crison S compact titrator, Crison Instruments, SA, Alella, Barcelona, Spain; expressed in grams of malic acid per liter), and starch pattern index (by Lugol staining) were measured on each fruit. Stained fruit sections were photographed and the same algorithm used for determination of peel color, was used to quantify staining. The output in this case is an index ranging from 0 (no staining) to 1 (fully stained).

At the beginning of October, trunk circumference was measured at about 15 cm above the graft union, trees were defoliated, all leaves of each tree were weighed, and a sub-sample of 30 leaves per tree was transported to the laboratory for determination of area, fresh and dry weight. The leaf sub-samples were photographed and their area was measured by digital image analysis; leaf area of sub-samples was used to establish a correlation with leaf weight and estimate total leaf area per tree. Trunk cross-sectional area and leaf area were used to calculate yield efficiency (kilogram of fruit per square centimeter of trunk cross-sectional area), crop load (number of fruits per square centimeter of trunk cross-sectional area), and fruit:leaf ratio (kilogram of fruit per square meter of leaf area). Subsequently, entire above-ground wood structures (trunk, limbs, and shoots) were cut at the ground level, and photographed with the digital camera against a white background from plan and side views for later acquisition of bi- and three-dimensional measurements. A measuring tape of known length was included in the picture as a reference for subsequent size adjustments. After all images were acquired, wood structures were cut, weighed, and oven-dried at 60°C to a constant weight. Digital images were edited as described by Lo Bianco *et al.* (2003) to determine total shoot length and diameter. Briefly, the background was manually removed from original JPEG images and clean images were saved as binary TIFF files. Morphological image processing (skeletonizing algorithm) was used to separate the seasonal growth from older wood according to diameter category. ROOTEDGE software (Iowa State University Foundation Inc., Ames, IA, USA) was used to scan TIFF images and determine shoot length and diameter.

The original images were also used to calculate average internode length (dividing shoot length by number of nodes) from three shoots per tree, canopy spread area (marked as a circle or ellipse enclosing all stems in the plan views), and canopy height. Canopy shape of the young apple trees resembled a cone. Hence, canopy volume was estimated as follows:

Volume = (spread area × height)/3

Canopy density was calculated as the total length of wood portions per unit of volume.

Yield, fruit quality, and growth data were compared by analysis of variance (with irrigation treatment and replicate as factors) using SYSTAT procedures (Systat Software Inc., Richmond, CA, USA). Fruit quality data were also analyzed using crop load or yield efficiency as covariate. Repeated measures analysis of variance followed by orthogonal polynomial contrasts was used to evaluate differences in g_s, soil water content, and fruit growth between treatments and sampling dates. Pearson product moment correlation analysis was used to determine associations between g_s, SWC, and VPD.

Results

The irrigation season started on 31 July (5 days after the last relevant precipitation event and 92 days after bloom) and ended on 13 September (Fig. 1A). The total irrigation volume was 90 mm for CI and 45 mm for FPRD distributed over 20 events. Daily vapour pressure deficit varied greatly reaching peaks of over 3 kPa on particularly hot and dry days and showing significant reductions (below 0.5 kPa) on corresponding rainy days (Fig. 1B).

Wet and dry soil areas showed significantly different SWC from 16 August until 14 September, with the exception of 7 September when a problem in the irrigation system caused skipping of one programmed event (Fig. 2A). On 16 September, similar SWC in wet and dry areas was due to over 10 mm of rain early in the same day (Fig. 1A). Repeated measures analysis showed a significant effect of the irrigation treatment ($P < 0.001$), a significant change of SWC over time ($P < 0.001$), and a significant interaction between irrigation treatment and SWC over time ($P = 0.004$) indicating that SWC was changing over time in a different fashion in the wet and dry areas. In particular, SWC in the dry areas decreased exponentially according to the model

$$SWC = 0.199 + 0.048\, e^{-0.205\ \mathrm{day}}\ (P < 0.001,\ r^2 = 0.940).$$

Stomatal conductance of CI and FPRD trees differed significantly from 24 August until the end of the sampling period (Fig. 2B). The effect of the irrigation treatment was significant ($P < 0.001$), conductance changed significantly over time ($P < 0.001$), and irrigation treatment x conductance over time interacted significantly ($P = 0.002$). Initial stomatal response to changes in SWC was delayed by about eight days (Fig. 2A and B). Stomatal conductance of FPRD trees was correlated to SWC (r = 0.888, $P = 0.001$) and VPD (r = 0.709, $P = 0.010$), whereas, conductance of CI trees was correlated only with SWC (r = 0.729, $P = 0.026$).

Repeated measure analysis indicated no significant effect of irrigation treatment on fruit cross-sectional area ($P = 0.392$; Fig. 3A), but there was a significant change of cross-sectional area over time ($P < 0.001$) and a significant interaction between irrigation treatment and change of cross-sectional area over time ($P < 0.001$). Specifically, the first degree (linear) polynomial contrast explained over 98% of the variability due to changes of cross-sectional area over time. On the other hand, relative growth rate of CI fruit was significantly greater than that of FPRD fruit on 27 and 31 August (Fig. 3B). In this case, repeated measure analysis showed a significant irrigation treatment effect ($P = 0.003$), a significant change of relative growth rate over time ($P < 0.001$), but no significant interaction between irrigation treatment and change of relative growth rate over time ($P = 0.330$). The first degree (linear) polynomial contrast explained over 80% of the variability due to changes of relative growth rate over time.

Trees in the two irrigation treatments had similar yields, number of fruit, crop load, and fruit:leaf ratio, but FPRD trees were more efficient than CI trees (Table 1). Using yield efficiency or crop load as a covariate in the analysis of variance for fruit quality

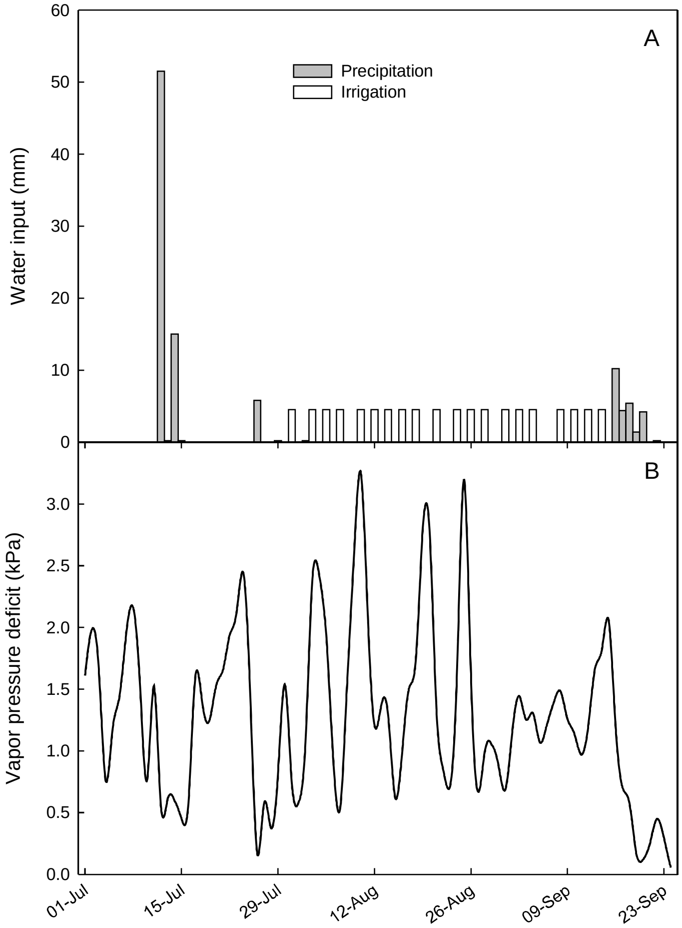

Fig. 1. Average daily water inputs (A) and vapor pressure deficit (B) during summer 2004 near Caltavuturo (37° 49’ N and 850 m above sea level), Sicily.

Table 1. Yield performance of six-year-old 'Golden Delicious' apple trees under conventional irrigation (CI) and fixed partial rootzone drying (FPRD)

Yield parameters	CI	FPRD	P^z
Yield (kg tree^{-1})	12.1	14.7	0.098
Number of fruits	103	135	0.068
Yield efficiency (kg cm^{-2})	0.31	0.39	0.046
Crop load (fruits cm^{-2})	2.61	3.56	0.062
Fruit:leaf ratio (kg m^{-2})	3.70	3.65	0.933

^{z} *P* value from analysis of variance.

Table 2. Fruit quality of six-year-old 'Golden Delicious' apple trees under conventional irrigation (CI) and fixed partial rootzone drying (FPRD)

Quality paremerers	CI	FPRD	P^z
Fresh weight (g)	125	115	0.133
Cross-sectional area (cm^2)	48.4	46.2	0.436
Peel color index	0.93	0.92	0.055
Flesh firmness (kg cm^{-2})	8.52	8.88	0.295
Starch pattern index	0.94	0.94	0.545
Soluble solids (°Brix)	12.2	12.1	0.506
Acidity (g L^{-1})	4.60	4.45	0.484
pH	3.63	3.70	0.276

^{z} *P* value from analysis of variance.

Table 3. Vegetative growth of six-year-old 'Golden Delicious' apple trees under conventional irrigation (CI) and fixed partial rootzone drying (FPRD)

Growth parameters	CI	FPRD	P^z
Tree height (m)	3.11	3.06	0.437
Wood fresh weight (kg)	8.07	7.73	0.586
Wood dry weight (kg)	4.17	4.13	0.904
Canopy spread area (m^2)	4.90	4.52	0.197
Canopy volume (m^3)	5.10	4.62	0.149
Canopy density (m m^3)	12.2	13.7	0.014
Shoot length (m)	49.6	50.2	0.854
Shoot diameter (cm)	0.69	0.66	0.017
Shoot number	182	176	0.588
Internode length (cm)	3.24	3.19	0.732
Leaf area (m^2 tree^{-1})	3.76	4.06	0.377
Leaf dry weight (kg tree^{-1})	0.47	0.62	0.003
Leaf specific weight (kg m^{-2})	0.13	0.15	<0.001
Leaf water content (%)	49.9	47.0	0.004

^{z} *P* value from analysis of variance.

parameters, did not affect differences between CI and FPRD trees. Hence original means and statistics from analysis with no covariate are reported in Table 2. In particular, quality parameters of fruit of CI and FPRD trees were similar (Table 2).

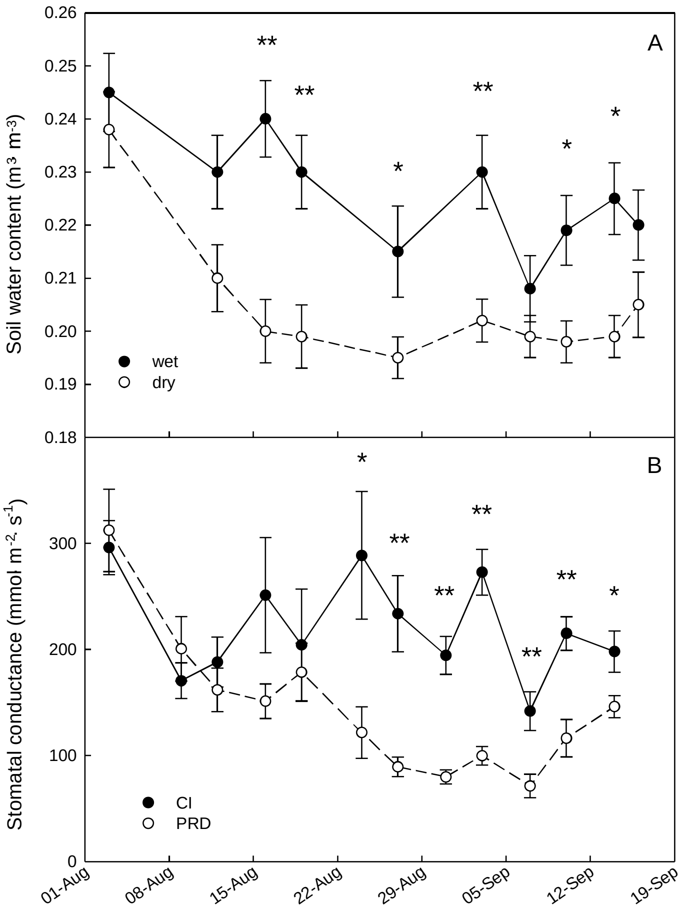

Fig. 2. Soil water content (A) and stomatal conductance (B) of six-year-old 'Golden Delicious' apple trees under conventional irrigation (CI) and fixed partial rootzone drying (FPRD). ** and * indicate significant differences between the two treatments at $P \leq 0.01$ and $P \leq 0.05$, respectively. Error bars represent standard errors of the means.

Vegetative growth showed some differences mainly due to a greater leaf water content in CI trees compared to FPRD trees. Statistically, CI and FPRD trees had similar height, wood fresh and dry weight, canopy spread area and volume, shoot length and number, internode length, and leaf area (Table 3). On the other hand, CI trees had thicker shoots and greater leaf water content, but lower canopy density, leaf dry weight and specific weight than FPRD trees (Table 3).

Discussion

This study provides further positive support in favour of PRD irrigation strategy over CI for apple cultivation in semi-arid environments in the Southern Mediterranean regions. In particular, a 50% reduction of the irrigation water applied during the entire season to only one side of the rootzone did not reduce yields compared to conventionally irrigated trees. Similarly, we did not detect any difference in fruit external or internal quality, whereas differences in water status (g_s) resulted in some reduction of vegetative growth of FPRD trees. In previous studies, there were no changes in fruit quality in response to PRD in 'Breaburn' (Van Hooijdonk *et al.*, 2004) and 'Gala' (Caspari *et al.*, 2004a) apple.

It took slightly over a week for the 'Golden Delicious' trees to reduce g_s in response to diminished soil water content. This might provide an indication of the time required for a six-year-old apple

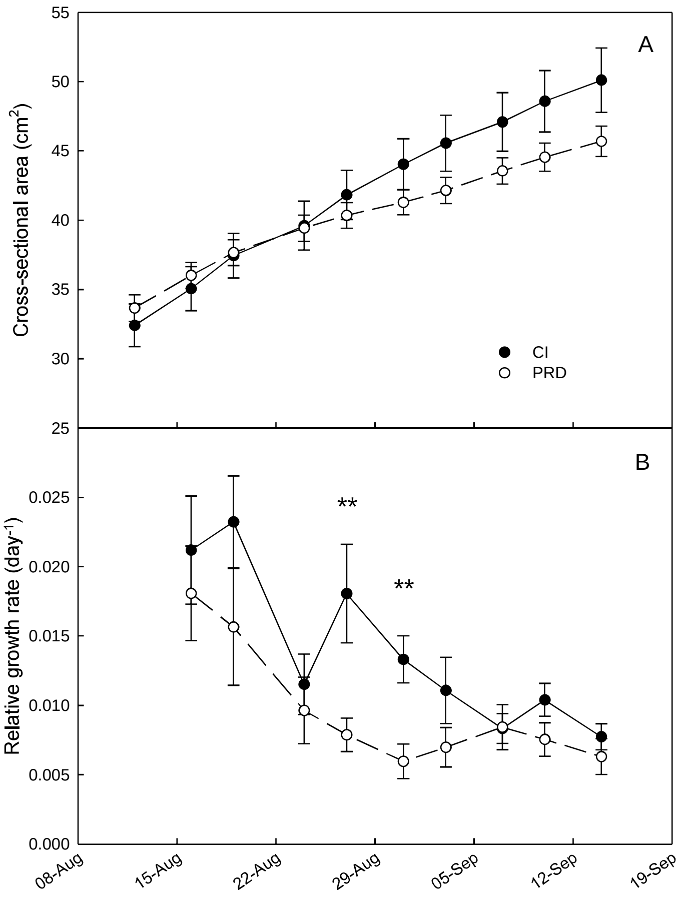

Fig. 3. Fruit cross-sectional area (A) and relative growth rate (B) of six-year-old 'Golden Delicious' apple trees under conventional irrigation (CI) and fixed partial rootzone drying (FPRD). ** and * indicate significant differences between the two treatments at $P \leq 0.01$ and $P \leq 0.05$, respectively. Error bars represent standard errors of the means.

tree to synthesize ABA in the root system and/or to translocate a sufficient amount of hormone to the leaves for the reduction in g_s to be detectable. Similar reductions in g_s have been reported in PRD apple (Gowing *et al.*, 1990), olive (Wahbi *et al.*, 2005), and grapes (De Souza *et al.*, 2003). Other studies with field-grown apple trees, however, have shown no reduction in g_s in response to PRD (Caspari *et al.*, 2004b; Einhorn and Caspari, 2004; Lombardini *et al.*, 2004; Van Hooijdonk *et al.*, 2004) so the ability of hormonal signals to reduce g_s may depend on the evaporative demand and the rate of transport of signals to the leaves (Davies *et al.*, 2002). Thus, the generally low irrigation volumes and relatively high evaporative demand during our experiment could explain differences between our results and previous studies.

In grapes, switching of the wet and dry sides every 10 to 15 days is needed to maintain the ABA signal and the consequent reduced g_s (Dry and Loveys, 1999; Loveys *et al.*, 2000). This is apparently due to the transient nature of ABA accumulation in grape roots in dry soil. In 'Fuji' apple grown in the semi-arid climate of Washington State, Leib *et al.* (2006) alternated wet and dry sides of the PRD treatment every 3-4 weeks without affecting fruit size or yield. In our study, although we did not switch wet and dry sides, g_s of FPRD trees remained significantly lower than that of CI trees for the final three weeks of the irrigation season. Probably, under our conditions a longer period of time was needed for a further decrease in SWC in the dry root zone side, and thus for the ABA signal to be canceled and for g_s to return to control levels.

In spite of the observed reductions in g_s of FPRD trees, mainly due to lower SWC, fruit growth rate was affected on only two dates and there was no difference in final fruit size, weight, yields, and fruit quality between the two irrigation treatments. Other authors have observed contrasting responses for apple fruit yield and quality depending on the season, orchard location, and climatic conditions; for example, Lombardini *et al.* (2004) observed a reduction in fruit size for apple trees under PRD. However, it is generally accepted that PRD does not affect apple fruit yield and quality (Caspari *et al.*, 2004a, b; Einhorn and Caspari, 2004; Van Hooijdonk *et al.*, 2004).

Our irrigation treatments resulted in thinner shoots and greater leaf specific weight in FPRD compared to CI trees but tree size and shape was not affected. Since wood dry weight was not influenced by irrigation, thinner shoots in FPRD trees may be the result of some reduction in shoot radial growth probably due to a decrease in the diameter of xylem elements. On the other hand, higher leaf specific weights in FPRD trees could be related to reduced cell expansion (probably due to the reduced water content), increase in cell number, and consequent increase in the deposition of cell wall structures. Growth reductions, mainly in terms of decreased shoot length, were reported in PRD raspberry (Grant *et al.*, 2004), grapes (Dry *et al.*, 2000; Santos *et al.*, 2003), olive (Wahbi *et al.*, 2005), and potted apple (Gowing *et al.*, 1990), but not in field-grown apple (Einhorn and Caspari, 2004; Lombardini *et al.*, 2004). In our case, the lack of reductions in shoot length in response to FPRD could be due to the late timing of treatment when flush of terminal shoot growth was nearly completed.

Timing of treatment imposition may have also played an important role in the behaviour of reproductive sinks. In other words, fruits may have escaped significant size reductions because most of the cell division had been already completed by 16 August when differences in SWC became significant. Fruit may have been stronger sinks for water than shoot tissues during final cell expansion. Similarly, late decreases in water potential did not reduce fruit size of 'Breaburn' apple (Kilili *et al.*, 1996).

This study suggests a potential advantage of using PRD strategies over CI in 'Golden Delicious' apple orchards for reduction of irrigation inputs in central Sicily. Continuation of field measurements in the following years with the addition of deficit irrigation treatments with reduced water amounts distributed to both sides of the rootzone and alternated PRD treatments, should allow for determination of any greater potential for PRD utilization as a common irrigation practice to save water in dry climates.

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