Above- and Belowground Responses to Shifts in Soil Moisture in Bearing Apple Trees

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Abstract. Limiting irrigation to increase fruit quality as well as conserve limited water resources is of increasing importance. We examined the links of aboveground growth and physiology to root growth and distribution under cultural practices associated with restricted irrigation and mulching in an apple ('Gala/M.9'; *Malus × domestica* Borkh.) orchard in a semiarid climate. Trees were either mulched to maintain a 10-cm depth or left unmulched. After orchard establishment, half the trees (partially irrigated) received daily drip irrigation only sufficient to meet 50% of daily evapotranspiration for 45 days before fruit harvest using one emitter per tree. The other trees continued to receive 100% irrigation using two emitters. Over three growing seasons, fruit yield was strongly affected in 2 of 3 years by partial irrigation if trees were unmulched but not if mulched. Fruit size and other quality parameters were minimally affected by partial irrigation. Total fine root length in fully irrigated trees was nearly double that of partially irrigated trees. Our results suggest that increases in soil moisture associated with mulching enabled mulched apple trees to tolerate deficit irrigation with minimal consequences for production and quality of apples, but with an overall less extensive and smaller root system.

Soil moisture deficits are one of the most important environmental factors influencing plant growth and reproduction. In many of the fruit-growing regions of the world, including western North America (Barnett et al., 2004), the future availability of water has been questioned as a consequence of climate change and variability. This problem is particularly acute in the southern British Columbia fruit-growing region, where conflicts have arisen between horticulture producers and domestic water users (Neilsen et al., 2006). Thus, for fruit crop production, there is increased interest in imposing controlled moisture deficits to reduce water use as well as limit vegetative growth while potentially improving fruit quality (Behboudian and Mills, 1997).

Manifestations of controlled deficit irrigation have been studied mostly in grape (Dry and Loveys, 1998) and, to a lesser extent, in other fruit crops, including apple (Leib et al., 2006; Mills et al., 1994). There have only been a few studies that investigated both whole-plant physiology and root

dynamics (Abrisqueta et al., 2008). Most studies indicate that root systems grow preferentially in moist regions of the soil and exhibit only limited growth in dry soil (Green and Clothier, 1999). However, depending on the volume of soil irrigated, fruit trees can exhibit high architectural plasticity by positioning roots in irrigated soil regions and limiting root growth in dry regions, with little or only relatively small reductions in overall plant water balance (Améiglio et al., 1999). When imposing deficit irrigation, the rate of occurrence of these shifts in root growth may be an important contributor to effective irrigation management, but has not been well studied under field conditions.

In this article, we examine the effects of mulching and restricting irrigation for a 45-d period late in the growing season (August and September) in each of three years on 'Gala' apples on M.9 rootstock in sandy soils in southern British Columbia, Canada. Investigations included root growth, shoot water relations, tree branch growth, and fruit yield. We hypothesized that restricted irrigation would increase root growth in the irrigated portion of the soil, and reduce aboveground vegetative growth with only modest reductions in stomatal conductance (g_s) and stem water potential. In addition, we

hypothesized that mulching would reduce the levels of water stress on the trees caused by restricted irrigation.

Materials and Methods

The experimental 'Gala/M.9' apple (*Malus domestica*) orchard was located at the Summerland Research Center in Summerland, British Columbia (lat. 49°34'N, long. 119°39'W; elevation, 500 m). Soils are Skaha loamy sand (Wittenben, 1986), an aridic Haploxeroll, which are characterized by limited nutrient- and water-holding capacities. The average available water storage capacity for this soil series is about 13%, with the volumetric moisture content averaging 21% by volume at field capacity (−0.01 MPa) and 8% at the permanent wilting point (−1.5 MPa) (Kowalenko et al., 2009). Trees were planted in April 1997 at a 1-m spacing in the row and 3-m spacing between the rows. The experimental design was a randomized complete block with each of six rows representing a replicate block. Within a row, the experimental plots were in groups of three 'Gala/M.9' trees with a border tree of 'Spartan/M.9' on either side. For plots receiving mulch, wood waste mulch was applied to maintain a depth of 10 cm in two plots per row in 1997, 1998, and 1999. Wood mulch was applied in the herbicide strip with a width of 1.5 m centered on the tree row. Each tree had two drippers, located 0.25 m on either side of the trunk within the tree row (i.e., 0.5 m apart). Irrigation occurred daily beginning near bloom and ending after harvest in late October. Irrigation was set to meet 100% of the previous day's estimated potential evapotranspiration using an atmometer (Parchomchuk et al., 1996). Trees were fertigated daily beginning in late May for 6 weeks to receive optimum complete fertility, which involved application of 150 mg N/L as CaNO_3 (15.5–0–0) with 25 g K/tree as KCl (0–0–62), 0.16 g B/tree as Solubor (20% B), 7 g Zn/tree as ZnSO_4 (36% Zn), and 24 g Mg/tree as MgSO_4 (10% Mg). One dripper was blocked in the partial irrigation plots at about 85 d after bloom and remained blocked for about 45 d in 2001–03. This time was selected to avoid water stress during cell division (which occurs during the first month after bloom), when apple fruit is particularly sensitive to water stress, and such stress has been documented to reduce harvest fruit size (Wünsche and Ferguson, 2004). Also, this later imposition of water stress occurs when evaporative transpiration is at a maximum, offering a potential for large water savings. This is also the time when calls for irrigation reductions are most likely to be made in irrigation districts, especially in years of extreme drought. Full irrigation (two emitters) was applied both to partially and fully irrigated trees otherwise. The total volume of water applied to fully and partially irrigated plots was measured for the 2001 and 2002 growing seasons, but no measurements were made in 2003 as a result of the theft of the data logger partway through the season. Fully irrigated trees received 967

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and 2134 L/tree compared with 785 and 1821 L/tree received by partially irrigated trees throughout the 2001–02 growing seasons, respectively.

In Mar. 2001, clear acrylic root observation tubes (minirhizotrons) were installed about 30 cm from the bole of each tree at an angle of 30° from the vertical, beneath the dripper and pointing toward the tree base. In plots that were to be partially irrigated, a minirhizotron tube was placed by both drippers of the measurement trees in the plot. For the plots receiving full irrigation, only one of the two drippers of each tree had a minirhizotron located beneath it. Minirhizotrons were 92 cm in length and 6 cm o.d., and were inscribed with a single vertical transect of seventy 1.6- × 1.1-cm windows on the upper surface. The bottoms of the tubes were sealed with PVC plugs. Light penetration and radiant heating were prevented by wrapping the tops of the tubes in black electrical tape, sealing them with rubber stoppers, and covering them with a white metal can. A total of 61 minirhizotrons were monitored during the experiment.

Beginning 16 July 2001 and every 1 to 2 weeks thereafter, until the end of each growing season (leaf fall), and monthly thereafter, a specially designed miniature video camera (BTC-2; Bartz Technology, Santa Barbara, CA) was inserted into the minirhizotrons and recorded images of the roots visible in the windows on Hi-8 videotape. The videotape images were then transferred to a computer where they were subsequently processed for root demographic information. Information collected from images included date of root initiation (Wells and Eissenstat, 2001).

After three field seasons in Oct. 2003, soil core samples (diameter, 7.5 cm) were collected at radial distances of 15, 30, and 45 cm from the trunk perpendicular to the tree row and at depths of 0 to 10, 11 to 20, 21 to 30, 31 to 40, 41 to 60, and 61 to 90 cm below the soil surface. Sampling in the partially irrigated plots was undertaken on both the wet and dry side of tree. For the fully irrigated plots, sampling was only taken on one side of the tree. Both mulched and unmulched trees were sampled. For all samples, all roots in the soil cores were separated by washing with water through 2-mm sieves. (Root length was determined by scanning the roots recovered at each depth and sample location.) Root length density (measured in centimeters per cubic centimeter) was estimated at each depth interval, and total root length (measured in centimeters per square centimeter) was estimated for each radial location by summing root length density over the total depth of sampling.

Stem water potential was monitored weekly (biweekly in 2003) beginning 1 d before initiating the partial irrigation treatment and continuing until the end of the season. Three leaves on one tree in each experimental plot (24 trees total) were measured. Stem water potential was determined by covering the leaf with black plastic and then aluminum foil 3 h before measuring it

with a pressure chamber (McCutchan and Shackel 1992). Water potential measurements were typically made between 1100 and 1300 HR.

Photosynthesis and g_s were determined in young, fully expanded leaves exposed to full sun with an open gas-exchange system (LI-COR 6400; LI-COR, Lincoln, NE), typically between 1300 and 1500 HR. Measurements were made weekly during the irrigation treatment periods in 2001–03. A forest fire in Aug. 2003 in the region reduced the number of usable photosynthesis readings in that year, so 2003 data for g_s and photosynthesis are not reported.

Soil moisture in all treatments was determined every 1 to 2 weeks during each growing season, integrated over a depth of 40 cm using time domain reflectometry (Tektronix, Beaverton, OR) (Topp and Davis, 1985). Probes were located midway between the tree bole and the emitter within the tree row. Soil temperature was determined at hourly intervals at a 10-cm depth using a thermistor and a HOBO® data logger (Onset, Bourne, MA) and these values were averaged to generate daily means.

At commercial harvest each year, yield and number of fruit harvested from each experimental tree were recorded, which allowed calculation of mean fruit size. Yield efficiency was calculated by dividing yield by trunk cross-sectional area, which was measured annually in the dormant season. A randomly selected 10-apple sample from the mid-canopy locations for each experimental tree was also evaluated annually for flesh firmness, skin red color, titratable acidity (TA), and soluble solids concentration (SSC). Flesh firmness was determined with a Baullaf (Lake City Technical Products Ltd., Kelowna, BC, Canada) penetrometer (11.1-mm diameter tip). Percent red skin color was estimated visually to the nearest 5%. Juice SSC was measured with a refractometer, and TA was determined by titration of juice with 0.1 M NaOH to an 8.1 pH endpoint and expressed as malic acid equivalents.

Analysis of variance was performed on all soil moisture, plant water relations, root production, yield, and fruit quality data as a factorial combination of two irrigation treatments (complete or partial) with and without mulching, with six replicate plots containing three trees each (SAS, 1989). Percent red color was arcsine-transformed before variance analyses. Minirhizotron cumulative root production data were log-transformed. Data were analyzed separately by year because of annual variation in fruit production and quality.

Results

Soil moisture. Cessation of irrigation by plugging one of the drip emitters resulted in large and rapid reductions in soil moisture content at a 0- to 40-cm depth below the dry side of the partial irrigation treatment for each year that irrigation was withheld from that half of the root zone in 2001–03 (Fig. 1). Decreased soil moisture content was evident

Fig. 1. Rainfall (bars) and volumetric soil moisture content (curves) beneath the irrigation emitter in a 'Gala' apple orchard under full and partial irrigation in plots that had been mulched (M) or unmulched (NM, no mulch) determined in 2001–03. Soil moisture was integrated over a 40-cm depth, midway between the emitter and bole of the tree. Error bars denote SE.

the day after treatment, with values declining to minimums ranging from 11% to 13% v/v within 14 d of treatment imposition. Restoration of watering resulted in rapid increases in soil moisture beneath the plugged emitters, although significantly decreased soil moisture ($P < 0.05$) content for these emitters was still measurable 12 d (2002) to 16 d (2003) after cessation of differential watering. There were no differences in moisture content between treatments on the final measurement of each growing season, indicating no differences in soil moisture status over the winter. In 2002 and 2003, moisture measurements were made more extensively, including before the establishment of the differential treatments. At these times, similar moisture contents—averaging about 20%—were observed for both emitters.

Presence of a mulch also affected soil moisture content, but differences during the deficit irrigation period were less than observed

between irrigation treatments (Fig. 1). Mulch generally provided a 2% to 3% increase in soil moisture content relative to unmulched soils, including outside the time period of emitter plugging during the more extensive measurements in 2002 and 2003 ($P < 0.05$).

Tree water relations and photosynthesis. g_s was the most frequent indicator of water stress, with significantly decreased values ($P < 0.05$) for trees undergoing partial as opposed to full irrigation for 11 of 15 measurement times throughout the study (Fig. 2). Initial differences in g_s values between treatments were not significantly different from each other. In general (aside from two occasions in the second year of the study), mulched trees did not exhibit increased g_s compared with unmulched trees. Partially irrigated unmulched trees often exhibited the lowest stem water potentials, although most of the significant differences (four of five occasions) were measured in the first year of the imposition of the stress. In the first year of treatment, stem water potentials in some of the unmulched, partially irrigated trees declined to less than -1.5 MPa (average, -1.4 MPa on 14 Sept. 2001). Stem water potential was only affected by mulching on 14 and 21 Sept. in the first year of the study, with greater stress (more negative values) indicated for unmulched trees on 14 Sept. and for unmulched trees but only with partial irrigation on 21 Sept. (significant irrigation-by-mulch interaction). However, the biologic relevance of such a short-term decrease in stem water potential is questionable. Net CO_2 uptake values were significantly affected by treatments during the first 2 years of the study and were consistent with patterns observed for the other two plant water relation metrics (Fig. 2). Compared with full irrigation, assimilation of C was reduced significantly by partial irrigation on 6 of 15 measurement occasions over the first 2 years. Most of the differences ($n = 4$) were observed in the first year. Elevated C assimilation was associated with mulching only twice at the end of the second year of the measurement cycle (Fig. 2).

Aboveground growth and fruit quality. The combination of differential, late-season irrigation treatments with or without mulch had no appreciable effects on tree shoot growth, estimated by winter pruning weights and average fruit size (Table 1). Tree fruit production (yield), however, was affected by a combination of deficit irrigation and mulching in the first and third years. We observed a significant yield reduction in unmulched but not mulched trees with partial root zone irrigation relative to trees receiving full irrigation. Lower fruit yield in the partially irrigated unmulched trees was linked to a smaller tree size, because yield efficiency was unaffected by treatments over the 3 years (Table 1).

Treatments had minimal effects on aspects of fruit quality, including fruit firmness, red color, soluble solids, and acidity (malic acid) (Table 2). The only exception was a significant interaction between irrigation

and mulch treatments in first year when a lower malic acid concentration was observed on fruit undergoing partial irrigation and growing on unmulched trees.

Root production and distribution. Minirhizotron data indicated that the seasonal pattern of root initiation over the whole soil profile was associated strongly with soil temperature, with a high incidence of root birth when soil temperatures exceeded about $10^\circ C$ (Fig. 3). We have included data collected from the first year after the installation of the minirhizotron tubes (2001). Although the data from 2001 supports the overall trends observed in the subsequent years, care should be taken in interpreting data from the first year of root production because adequate time was not allowed for sufficient equilibration in root production after the initial disturbance caused by the installation of the tubes. Peak root production occurred from June to September, with minimal root production from December to March. Furthermore, the presence or absence of mulch did not alter timing of root production appreciably. Overall, the greatest cumulative annual root production occurred for the trees in the fully irrigated treatment in year 2002 ($P = 0.01$) and with a similar trend in 2003 ($P = 0.11$). There was no clear evidence of preferential root production on the wet side of the partially irrigated trees relative to the dry side during the brief annual periods when the emitter was plugged (Fig. 3). However, root production beneath the unplugged rather than the plugged emitter was greater before and after the period of drought imposition, including early Spring 2002 and 2003, and Oct. 2003 at the end of the experiment.

Root distribution measurements determined by coring to a 90-cm depth at the end of the experiment (Oct. 2003) indicated high variability in root length density among treatments, but the bulk of root length occurred within the upper 40-cm depth (Fig. 4). Limited root length was located deeper than 40 cm. Both irrigation and the depth of the core sample significantly affected root length density significantly, with more root length per unit volume occurring under irrigation and at shallower depths (full irrigation vs. partial, $P = 0.01$; depth, $P < 0.0001$). The only evidence of preferential root growth on the wet side of the partially irrigated trees occurred in the mulched treatments. This pattern was apparent whether coring was undertaken at a 15-, 30-, or 45-cm radial distance from the tree. When examining the partial irrigation treatments alone, both depth of the core sample ($P < 0.0001$) and radial distance ($P = 0.04$) affected root length density, with root length density declining with depth and radial distance from the trunk. Last, there was a significant interaction between the partial irrigation and mulch treatments ($P = 0.008$). Fully irrigated trees had more than twice the total root length compared with partially irrigated trees. When looking at the fully irrigated trees alone, depth—but not radial distance—diminished root length density significantly ($P < 0.05$).

Discussion

Soil water content. In the loamy sandy soil that characterized the experimental site, plugging one of the two emitters supplying water to each tree provoked a rapid drying response (in a matter of a few days) in the upper 40 cm of the soil beneath the blocked emitter. Previous root trench observation studies have indicated that this depth is likely to contain a greater proportion of total roots for apple trees grown on M.9 rootstock under daily drip irrigation on similar coarse-textured soils (Nielsen et al., 1997). The rapidity of the response can be attributed to the limited water-holding capacity of these soils and the high evapotranspiration at this time of year. Previous deficit irrigation studies have indicated a slower decline (weeks) toward minimum soil moisture contents for finer textured soils (58% silt and clay) with 23% moisture-holding capacity (Girona et al., 2010) and for deficit irrigation treatments imposed early in the season (Leib et al., 2006). During our 3-year study the, minimum root zone moisture content approached but did not reach the 8% volumetric water content associated with the permanent wilting point threshold (-1.5 MPa soil water potential) and, upon commencement of irrigation, rapidly returned to values similar to emitters receiving daily irrigation. Volumetric water content values fluctuated at levels slightly less than 21%, the value corresponding with field capacity (-0.033 MPa) for this soil.

Plant water relations and photosynthesis. Collectively, the tree water relations and photosynthesis data suggest that trees were stressed more by plugging one emitter later in the growing season in the absence of mulch than with mulch, and effects were most pronounced in the first year that irrigation treatments were imposed. Minimum g_s readings, which approached $0.1 \text{ mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ under the semiarid growing conditions in British Columbia, were similar to minimum values measured in a semiarid fruit growing region of Australia, where a season-long 50% deficit irrigation strategy resulted in reduced g_s in the first year of a 2-year study (O'Connell and Goodwin, 2007). In part, reductions in g_s can reflect reduced leaf and stem water potential (Garnier and Berger, 1987). In our study in British Columbia, significant reductions in midday stem water potential, which were concentrated mostly in the first year of this study and associated with the partial (deficit) irrigation strategy, reached minimum values ranging from -1.0 to -1.3 MPa. In comparison with other studies, these values would be considered to result in minimal stress, because reduced photosynthesis is generally reported when leaf potential of deficit-irrigated apple trees approaches -1.8 to -2.5 MPa (Mills et al., 1994; van Hooijdonk et al., 2004). Previous research has also indicated that, despite intense drought conditions, leaf potential can remain high under heterogeneous soil moisture conditions (Améglio et al., 1999), as would occur when irrigating

Fig. 2. Seasonal patterns of aboveground physiologic responses to soil moisture deficits with and without mulching. First row is stem water potential in 2001, 2002, and 2003, where the period of deficit irrigation is indicated by a horizontal line, the second row is leaf carbon assimilation, and the third row is leaf stomatal conductance. Asterisks indicate significant differences for that date between partial and full irrigation; pound sign indicates significant differences between mulch and no mulch (* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$). Vertical error bar indicates pooled SE across treatments on that date.

Table 1. Tree pruning weights, average fruit size, yield, and yield efficiency as affected by irrigation regimes and presence (+) or absence (–) of mulch over three growing seasons.

Treatments	2001				2002				2003 ²			
	Pruning wt (kg/tree)	Fruit size (g/fruit)	Yield (kg/tree)	Yield efficiency (kg·cm ⁻²)	Pruning wt (kg/tree)	Fruit size (g)	Yield (kg/tree)	Yield efficiency (kg·cm ⁻²)	Fruit size (g)	Yield (kg/tree)	Yield efficiency (kg·cm ⁻²)	
Irrigation regime ³			M (+) M (–)							M (+) M (–)		
Full	1.1	189.5	15.0 17.0	1.1	1.4	171.9	16.0	0.7	172.6	10.7 13.1	0.5	
Partial	1.0	177.8	16.8 11.0	1.3	0.7	164.8	13.9	0.7	173.2	12.4 9.2	0.5	
Significance	NS	NS		NS	NS	NS	NS	NS	NS		NS	
Mulch ⁴												
Present (+)	1.3	186.0		1.2	1.2	173.5	14.8	0.7	177.6		0.5	
Absent (–)	0.8	180.6		1.2	0.8	163.2	15.1	0.7	167.7		0.6	
Significance	NS	NS		NS	NS	NS	NS	NS	NS		NS	
I × M	NS	NS	**	NS	NS	NS	NS	NS	NS	*	NS	
SE ⁵			1.1							1.1		

²No pruning weights measured in third year.

³Complete irrigation comprised a daily drip, two emitters per tree at 100% estimated evaporative transpiration. Partial irrigation involved plugging of one emitter per tree for about 45 d about 85 d after bloom.

⁴Application of wood waste to maintain a 10-cm depth (1997–99).

⁵Interaction SE when statistically significant (* $P < 0.05$, ** $P < 0.01$).

I = irrigation regime; NS = nonsignificant; M = mulch.

half the root zone. Despite greater stem water potentials measured in our British Columbia study, significant reductions in net C assimilation were sometimes associated with deficit-irrigated trees, particularly in the first year.

Aboveground growth and fruit quality. Deficit irrigation, imposed late in the season to one side of the tree for about 6 weeks annually for 3 years, had few effects on apple yield efficiency and quality, especially if the

trees were mulched. Previously comparisons between fully irrigated and unirrigated apple trees has indicated increased soluble solids and accelerated maturity on water stressed ‘Braeburn’ fruit (Mills et al., 1994). This was

Table 2. Fruit quality as affected by irrigation regimes and presence (+) or absence (–) of mulch over three growing seasons.

Treatments	Firmness (N)			Red color (% solid red)			Soluble solids (%)			Malic acid (g/100 mL)		
	2001	2002	2003	2001	2002	2003	2001	2002	2003	2001	2002	2003
Irrigation regime ^z										M (+)	M (–)	
Full	86.2	82.0	86.8	55	90	80	11.7	13.2	12.7	0.46	0.47	0.45
Partial	87.4	83.4	87.2	50	90	90	12.4	13.6	12.7	0.45	0.41	0.46
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS		NS	NS
Mulch ^y												
Present	86.6	81.9	86.5	50	90	85	12.1	13.4	12.6		0.45	0.42
Absent	87.0	83.6	87.6	55	90	90	12.0	13.4	12.8		0.46	0.41
Significance	NS	NS	NS	NS	NS	NS	NS	NS	NS		NS	NS
I × M	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	NS
SE ^x										0.01		

^zComplete irrigation comprised a daily drip, two emitters per tree at 100% estimated evaporative transpiration. Partial irrigation involved plugging of one emitter per tree for about 45 d about 85 d after bloom.

^yApplication of wood waste to maintain a 10-cm depth (1997–99).

^xInteraction SE when statistically significant (* $P < 0.05$, ** $P < 0.01$).

I = irrigation regime; NS = nonsignificant; M = mulch.

Fig. 3. Seasonal patterns of root production in 'Gala' apple trees under full and partial irrigation in plots that had been mulched or unmulched from 2001–03. Error bars denote SE. Partially irrigated trees had one of the two emitters plugged for 45 d before fruit harvest. For partially irrigated trees, root observations were made both underneath the plugged emitter and underneath the irrigation emitter that worked normally. Arrows on the top axis indicate the time irrigation began each year. Shaded panels indicate the period during which irrigation was prevented on one side of the partially irrigated trees. The bottom row shows the trace of soil temperature at a 10-cm depth and precipitation at the site. Asterisks indicate significant differences for that date between partial and full irrigation; pound sign indicates significant differences between mulch and no mulch (* $P < 0.05$, *** $P < 0.01$, **** $P < 0.001$). Vertical error bar indicates pooled SE across treatments on that date.

measured in a study in which a season-long treatment comparison was made over a single year. In a study more comparable to ours on 'Pink Lady', a 50% water application via

microjet to one side was compared with a 100% irrigation (both sides) and resulted in decreased apple fruit size and yield, but only in the first year of a 2-year study

(O'Connell and Goodwin, 2007). Again, this represented a season-long comparison. Leib et al. (2006) initiated partial and deficit irrigation treatments 40 d after full bloom to minimize negative consequences to fruit size and quality while reducing water application rates. Deficit irrigation treatments were maintained annually for 3 years until harvest, with apple yield reduced by the 50% deficit irrigation treatment applied to both side of the tree, only once over three seasons. In our study, the short-term 6.5-week preharvest deficit irrigation reduced orchard water applications by 19% (year 1) and 15% (year 2), with minimal impact on yield and fruit quality, especially if trees were mulched.

Root production and distribution. Although root zone dynamics have been shown to be important for water uptake of fruit trees (Green and Clothier, 1999), there have only been a few studies that have monitored root growth during periods of deficit irrigation (Abrisqueta et al., 2008). Our data suggest that cessation of irrigation to half the root volume of trees immediately before harvest occurs at a time when root initiation is normally active as a result of sufficiently warm soil temperatures. The high proportion of roots located within the surface 40 cm of the soil profile meant that potential water stress conditions could be achieved rapidly beneath the drip emitters over an important part of the overall root system. The importance of the 0- to 40-cm depth for potential apple tree water uptake has been observed previously (Green and Clothier, 1999) including for fertigated, daily drip-irrigated apple trees growing in coarse-textured soil (Nielsen et al., 1997). Continuous season-long deficit irrigation reduced root length density in a single year by more than 70% for peach trees with the greatest root density recorded under conditions of nonlimiting irrigation (Abrisqueta et al., 2008). Similarly, in our study, root production was greatest under full irrigation. However, reduced root production beneath the plugged compared with the unplugged emitter was more apparent outside the time of plugging rather than during the short time of imposed stress. Additional evidence of preferential growth on the wet side relative to the dry side could

Fig. 4. Root length density distribution ($\pm$ SE) to a 0.9-m soil depth at three distances from the bole (15, 30, and 45 cm) in 'Gala' apple trees perpendicular to the row center after 3 years of either full and partial irrigation in plots that had been mulched or not. Roots were sampled in Oct. 2003. Shading indicates sides of tree that were either irrigated or not (note that in fully irrigated trees, the right and left panels are the same, because only one side was sampled). The number in each panel ($\pm$ SE) indicates the cumulative root length (measured in centimeters per cubic centimeter) to a 0.9-m depth at each location.

be observed for the mulched trees when examining root distribution after 3 years at the end of the experiment. This compensatory growth may have contributed to the modest differences in plant water relations between fully and partially irrigated trees after the first year. Although the reduced root growth in partially irrigated trees may represent a slight C savings on belowground C expenditures, it likely only marginally offset the slightly reduced C gain associated with diminished leaf area and leaf photosynthesis. Nonetheless, the overall slight reductions in yield by the partial irrigation, especially in the mulched treatment, suggest overall tree C status was sufficient to meet reproductive demands.

Conclusions

Reduction of irrigation of 50% by plugging one of the two emitters annually before harvest for 3 years resulted in both a rapid decrease in soil moisture content throughout the surface 40 cm around the plugged emitter and an annual water savings of as much as 20% per tree. Decreased g_s was the most sensitive indicator of reduced water availability for the partially irrigated trees, although reduced midday stem water potential and C assimilation were also detected. Plant water relations were affected most during the first year of the study. The short-term deficit irrigation strategy had few significant effects

on aboveground growth, including tree vegetative growth, yield, fruit size and fruit quality parameters of firmness, red color, soluble solids, and malic acid content. At the end of the experiment, roots were distributed mostly between the surface and a 40-cm depth that had decreased soil moisture content upon emitter plugging. There was evidence of preferential root growth to the wet side of the partially irrigated trees, but only if they were mulched.

The presence of mulch was unable to prevent the decline of soil moisture content beneath the plugged emitter during partial irrigation, but was able to maintain a 2% to 3% increase in volumetric soil moisture content relative to continuous, daily irrigation, including during most of the growing season when no differential irrigation treatments were applied. The effect of mulch on tree aboveground and belowground growth was limited to an interaction with the irrigation treatment. Trees undergoing partial irrigation without mulch had a reduced yield (2 of 3 years) and fruit with a lower malic acid content (1 year).

The cumulative evidence suggests that short-term partial irrigation is a desirable conservation irrigation strategy. Its strategic imposition during a period of normally high evapotranspiration and high-water use allowed for reductions in annual water applications by 20%, with minimal effects on high-density apple tree growth, production,

and fruit quality, especially if trees were mulched. Its sustainability may be enhanced by compensatory root growth both on the wet side of mulched trees and on the dry side (with plugged emitter) when irrigation is reapplied. Particularly for orchards without mulch, reductions in root length density may increase risks to long-term sustainability of the apple trees.

Literature Cited

- Abrisqueta, J.M., O. Mounzer, S. Álvarez, W. Conejero, Y. Garcia-Orellana, L.M. Tapia, J. Vera, I. Abrisqueta, and M.C. Ruiz-Sanchez. 2008. Root dynamics of peach trees submitted to partial rootzone drying and continuous deficit irrigation. *Agr. Water Mgt.* 95:959-967.
- Améglio, T., P. Archer, M. Cohen, C. Valancogne, F.A. Daudet, S. Dayau, and P. Cruiziat. 1999. Significance and limits in the use of predawn leaf water potential for tree irrigation. *Plant Soil* 207:155-167.
- Barnett, T., R. Malone, W. Pennell, D. Stammer, B. Semtner, and W. Washington. 2004. The effects of climate change on water resources in the west: Introduction and overview. *Clim. Change* 62:1-11.
- Behboudian, M.H. and T.M. Mills. 1997. Deficit irrigation in deciduous orchards. *Hort. Rev.* 21:105-131.
- Dry, P.R. and B.R. Loveys. 1998. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. *Austral. J. Grape Wine Res.* 4:140-148.
- Garnier, E. and A. Berger. 1987. The influence of drought on stomatal conductance and water

- potential of peach trees growing in the field. *Scientia Hort.* 32:249–263.
- Girona, J., M.H. Behboudian, M. Mata, and J. del Compo. 2010. Exploring six reduced irrigation options under water shortage for ‘Golden Smoothee apple’: Responses of yield components over three years. *Agr. Water Mgt.* 98:370–375.
- Green, S. and B. Clothier. 1999. The root zone dynamics of water uptake by a mature apple tree. *Plant Soil* 206:61–77.
- Kowalenko, C.G., O. Schmidt, E. Kenney, D. Neilsen, and D. Poon. 2009. Okanagan Agricultural Soil Study 2007–A survey of the chemical and physical properties of agricultural soils of the Okanagan and Similkameen Valleys in relation to agronomic and environmental concerns. British Columbia Min. of Agric. and Lands. Nov. 2010.
- Leib, B.G., H.W. Caspari, C.A. Redulla, P.K. Andrews, and J.J. Jabro. 2006. Partial rootzone drying and deficit irrigation of ‘Fuji’ apples in a semi-arid climate. *Irr. Sci.* 24:85–99.
- McCutchan, H. and K.A. Shackel. 1992. Stem-water potential as a sensitive indicator of water stress of prune trees (*Prunus domestica* L. cv. French). *J. Amer. Soc. Hort. Sci.* 117:607–611.
- Mills, T.M., M.H. Behboudian, P.Y. Tan, and B.E. Clothier. 1994. Plant water status and fruit quality in ‘Braeburn’ apples. *HortScience* 29:1274–1278.
- Neilsen, D., C.A.S. Smith, G. Frank, W. Koch, Y. Alila, W.S. Merriitt, W.G. Taylor, M. Barton, J.W. Hall, and S.J. Cohen. 2006. Potential impacts of climate change on water availability for crops in the Okanagan Basin, British Columbia. *Can. J. Soil Sci.* 86:921–936.
- Neilsen, G.H., P. Parchomchuk, R. Berard, and D. Neilsen. 1997. Irrigation frequency and quantity affect root and top growth of fertigated ‘Mcintosh’ apple on M.9, M.26 and M.7 rootstock. *Can. J. Plant Sci.* 77:133–139.
- O’Connell, M.G. and I. Goodwin. 2007. Response of ‘Pink Lady’ apple to deficit irrigation and partial rootzone drying: Physiology, growth, yield, and fruit quality. *Austral. J. Agr. Res.* 58:1068–1076.
- Parchomchuk, P., R.C. Berard, and T.W. Van Der Gulik. 1996. Automated irrigation scheduling using an electronic atmometer, p. 1099–1104. In: C.R. Camp, E.J. Sadler, and R.E. Yoder (eds.). *Evapotranspiration and irrigation scheduling*. ASAE Proceedings of International Conference, San Antonio, TX.
- SAS. 1989. SAS/STAT: User’s guide. Ver. 6, vol. 2. SAS Institute, Cary, NC.
- Topp, G.C. and J.L. Davis. 1985. Measurement of soil water content TDR: A field evaluation. *Soil Sci. Soc. Amer. J.* 49:19–24.
- van Hooijdonk, B.M., K. Dorji, and M.H. Behboudian. 2004. Responses of ‘Pacific Rose’™ apple to partial rootzone drying and deficit irrigation. *Eur. J. Hort. Sci.* 69:104–110.
- Wells, C.E. and D.M. Eissenstat. 2001. Marked differences in survivorship among apple roots of different diameters. *Ecology* 82:882–892.
- Wittenben, U. 1986. Soils of the Okanagan and Similkameen Valleys. Ministry of the Environment Technical Report 10. British Columbia Soil Survey Report 52, Victoria, BC, Canada.
- Wünsche, J.N. and I.B. Ferguson. 2004. Crop load interactions in apple, p. 231–290. In: J. Janick (ed.). *Horticultural reviews*. Vol. 31. Wiley, Oxford, UK.