WTFRC Project # AH-02-206A Penn State Project: 404-66 WTFRC Soil Moisture 39E8

Project Title: Towards a better understanding of soil moisture deficits on shoot & root physiology

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Objectives:

- Describe patterns of seasonal root growth and mortality in apple trees on M9 rootstock in the Pacific Northwest
- Contrast root and shoot physiological responses for trees exposed to partial irrigation with those of well-watered controls, with and without mulch
- Contrast root and shoot physiological responses for trees exposed to deficit irrigation, partial root zone drying and well-watered controls.
- Contrast yields and fruit quality of trees exposed to deficit irrigation, partial root zone drying and well-watered controls.

Significant Findings:

- Seasonal patterns of root growth can vary considerably from year to year and is strongly affected by cultural practices. Little root growth occurred over winter and typically began in the spring around bloom time. Fully irrigated trees tended to grow roots in late summer, whereas partially irrigated trees typically exhibited limited root growth in July and August. In two of the three years of the study, an additional fall peak of root growth occurred in October.
- Compared to 100% replacement of daily ET, irrigating only one side of the tree with 50%

ET had generally little negative effect on fruit quality or yield, especially if trees were mulched. Where trees were not mulched, partial irrigation reduced stem water potentials, tended to reduce pruning weights but also reduced yields from about 12-36%. Fruit size was modestly reduced in the first year but not in 2002 or 2003. Mulched trees exhibited no negative effects from partial irrigation.

- Partial root zone drying (alternating sides) was less effective than irrigating only one side of the tree continuously as indicated by reduced fruit yields and tendency towards smaller fruit size by the second year of the study. This was attributed to less root growth in the one-side only treatment and higher stem water potentials.
- Neither partial root zone drying nor one-side only irrigation improved fruit quality over that observed in the well-water controls in the first two years of this research. Shoot vegetative growth was also not significantly affected by the irrigation treatments.

Methods:

Experiment 1: Mulch x partial irrigation:

This experiment compares the effect of partial irrigation in a 6-yr-old Gala/M9 experimental block at PARC Summerland where a mulching treatment had been previously imposed. For plots receiving mulch, wood waste mulch was applied to maintain a depth of 10 cm (4 inches) in two plots per row in 1997, 1998, and 1999. Each tree had two drippers, located on either side of the trunk and about 0.5 m apart. Irrigation occurred daily, beginning in early May and ending in mid Oct. Irrigation was set to meet 100% of the previous day's estimated potential evapotranspiration. Trees were fertigated daily beginning in late May for 9 weeks. One dripper was blocked in the partial irrigation plots on about 85 d after bloom and remained blocked for about 45 d in 2001-2003.

In March 2001, clear acrylic root observation tubes (minirhizotrons) were installed about 30 cm from the bole of each tree at an angle of 30º from the vertical, beneath the dripper and pointing towards the tree base. In plots that were to be partially irrigated, a tube was placed by both drippers of the 1-2 measurement trees in the plot; for the plots receiving full irrigation, only one of the two drippers of each tree had a root tube located beneath it. A total of 61 minirhizotrons were monitored in 2001.

A specially designed miniature video camera (BTC-2, Bartz Technology, Santa Barbara, CA) was inserted in the minirhizotrons and used to record images of roots visible in the windows on Hi-8 videotape or in 2002, digital tape. Images were collected every 1-2 weeks from June – Nov 2001, every 4 weeks until end of April, and then resumed every 1-2 weeks in May. The images on the tapes were transferred to a computer where they were subsequently processed for root births, deaths, and lifespan. Information collected from images includes date of root birth, root diameter, date of root pigmentation and date of root death by soil depth (Wells and Eissenstat 2001).

Stem water potential and leaf gas-exchange parameters were monitored weekly beginning 1 day prior to initiating the partial irrigation treatment and continuing until Oct. 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 prior to measuring it with a pressure chamber. Water potential measurements were typically made between 1100 and 1300 h. Photosynthesis, transpiration and stomatal conductance were determined on recent, fully expanded leaves exposed to full sun with an open gas-exchange system, typically between 1300 & 1500 h.

Soil moisture was determined weekly to a depth of 40 cm using time domain reflectrometry. Soil temperature was determined at hourly intervals at a 10-cm depth using a thermistor and a HOBO® data logger. Other standard climatic data were determined on site at a certified national weather station.

Experiment 2: Partial root zone drying and deficit irrigation
This study compared partial root zone drying with deficit irrigation in Golden Delicious trees on M9 rootstock. Two years of data have been collected—we are requesting funding for one more year.

Trees were planted in a 1-m spacing in sandy loam soil in April 1997. There were two drippers per tree, on either side of the bole, and about 50 cm apart. There were four treatments:

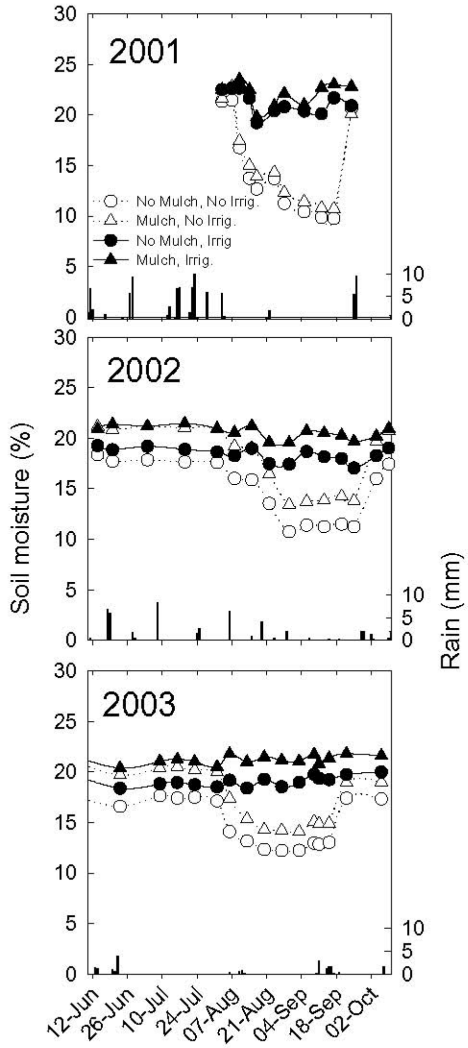
1. Full irrigation control where both drippers will be operative the full growing season (2 sides, 100% ET replacement).
2. Irrigation with both drippers but at a rate of only 50% of that in the other treatments (2 sides, 50% ET replacement).
3. Deficit irrigation where one dripper will be plugged from about 42 d after bloom (July) until harvest (1 side, 50% ET replacement). Before the July treatment and after harvest, normal irrigation (100% ET replacement).
4. Partial root zone drying, where irrigation by a specific dripper will only last one week and then it will turn off and the other dripper will be turned on. Thus, in this treatment soil is only allowed to dry for 7 d before the dripper is turned back on. This treatment will also begin 42 d after bloom and last until harvest (alternating sides, 50% ET replacement). Before the July treatment and after harvest, normal irrigation (100% ET replacement).

This experiment examined the effects of different irrigation practices on apple growth and physiology. The experiment was conducted on Golden Delicious/M9 border trees planted in sandy loam at a 1-m spacing in the row and 3 m between the rows in April, 1997. Acrylic minirhizotron tubes, similar to those used in the previous experiment, were installed in spring, 2002. There were two emitters per tree, on either side of the bole, and about 50 cm apart. There were four treatments in 5-tree plots with six replications of each treatment arranged in a randomized complete block design. The treatments were: (1) both emitters at full irrigation (100% previous day's ET), (2) both emitters (50% ET), (3) partial irrigation with only one emitter (50% ET), and (4) one emitter alternating from one side of the tree to the other (PRD, 50% ET). In the control treatment (1), we applied twice the amount of water as in the other three treatments. Treatments 2, 3 and 4 had the same amount of water but were spatially distributed differently over the season. Theoretically, the "partial root zone drying (PRD)" treatment should not lead to a reduction in stem water potential, only a loss in stomatal conductance. We chose a duration of approximately one week because this was the amount of time we found it took to appreciably dry down this soil.

Results and Discussion:

Experiment 1: Mulch x partial irrigation:
The partial irrigation experiment (50% ET daily replacement) was initiated on established trees that had been previously drip irrigated on both sides of the tree. This irrigation treatment moderately stressed the unmulched trees in the first year but the stress diminished in subsequent years as the trees adjusted their root system to shifts in water supply. Within each irrigation treatment, mulched trees exhibited higher soil water content (Fig. 1) and higher stem water potentials (Fig. 3) and higher carbon assimilation rates (Fig. 3). Mulching increased yields and pruning weights only in the partially irrigated treatments (Fig. 2). Fruit quality was generally unaffected by either irrigation or mulching (data not shown).

Daily root growth was higher in the mulch than unmulched treatment over the year (Fig. 4). During the irrigation treatment period (mid July through September) fully irrigated trees exhibited appreciable root production but very little root growth occurred in the partially irrigated trees in the unmulched soil, even though these trees were the most water stressed. This suggests that if photosynthesis is limiting during the fruit filling period, allocation is primarily to the fruit and not to the roots.



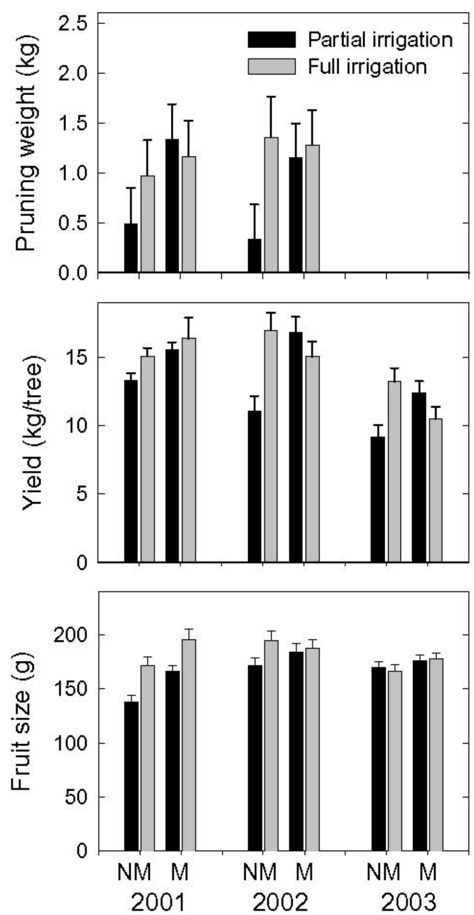


Fig 2. Pruning weights, fruit yield and fruit size (+SE) in Gala/M9 trees mulched (M) or

Fig 2. Pruning weights, fruit yield and fruit size (+SE) in Gala/M9 trees mulched (M) or not (NM) and partially irrigated (one-side, 50% ET) or fully irrigated both sides, 100% ET). Pruning weights determined in March or April of the following year. Trees were harvested after fruit harvest in October, 2003, so no pruning weights could be determined that year.

Fig 1. Soil water content (determined by TDR) of partially (dry side only) and fully irrigated (100% ET) Gala/M9 trees in mulched and unmulched treatments. Trees were planted in sandy loam soil in Summerland, BC. Rainfall also indicated by bars and right-axis scale.

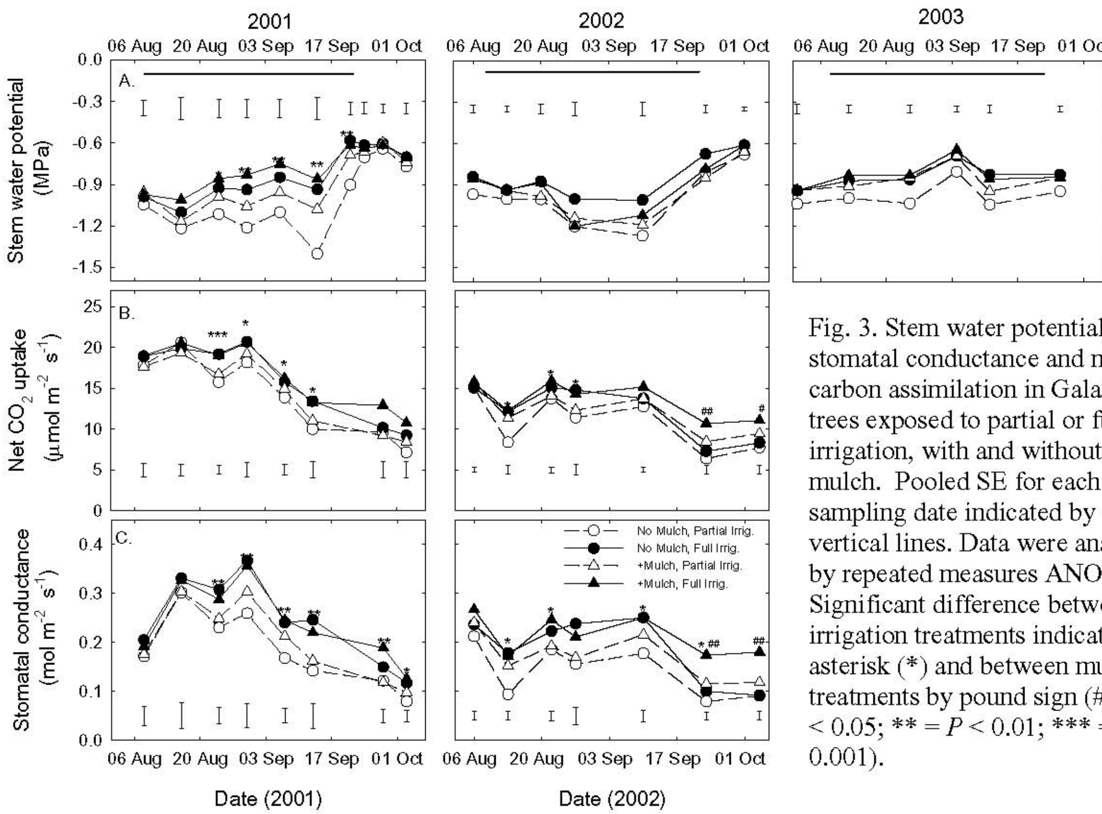


Fig. 3. Stem water potential, stomatal conductance and net carbon assimilation in Gala/M9 trees exposed to partial or full irrigation, with and without mulch. Pooled SE for each sampling date indicated by vertical lines. Data were analyz by repeated measures ANOVA. Significant difference between irrigation treatments indicated b asterisk (*) and between mulch treatments by pound sign (#)(* = < 0.05; ** = $P < 0.01$; *** = $P <$ 0.001).

Roots were harvested after fruit harvest in October, 2003 to determine root distribution in the experiment (Fig. 5). The partial irrigation in the mulch treatment indicated that after three years, a large fraction of roots were now on the irrigated side of the tree (top panels). There was little evidence, however, of long-term preferential root growth in the partially irrigated, unmulched treatment (panels 2nd from top). Root length densities were highest in the fully irrigated treatments, especially 30 cm from the trunk. The data indicated that water stressing trees in July – September did not result in greater root densities as often been proposed.

Experiment 2: Partial root zone drying and deficit irrigation

Summer rainfall was much higher in 2004 than in 2003, which somewhat disrupted the irrigation treatments in 2004 (Fig. 3). Full irrigation (Both, 100%) maintained soil water content over the summer of 2003; however, there were some summer days of 2004 when soil water content was 12%. The *Both-50%* treatment caused soil water content to fluctuate at about 5-7% in 2003. In the PRD (alternating) treatment the results are similar for both years, soil dried down within a 1-week period and then was irrigated. When the soil was dry, it was similar to the dry side of the *one-side* irrigation treatment. For both years the irrigated side of the PRD treatment was about 2% lower soil water content than the *one-side, Wet.*

The slightly higher soil water content on the *one-side*, continuously irrigated treatment presumably was the reason for the slightly higher stem water potentials in the *one-side* treatment than the *alternating* (PRD) treatment in 2003 and 2004 (Fig. 7a & 7b). We saw little difference in stomatal conductance or transpiration between the *one-side* and *alternating* treatments in 2003 (Fig. 7b, c). However, by 2004, stomatal conductance and transpiration were higher in the *one-side* than *alternating* treatments. **Thus, our results to date indicate that for the same amount of limited water, watering one side continuously is the best strategy, watering both sides is**

the worst strategy, and the *alternating* (PRD) strategy is intermediate in maintaining plant water

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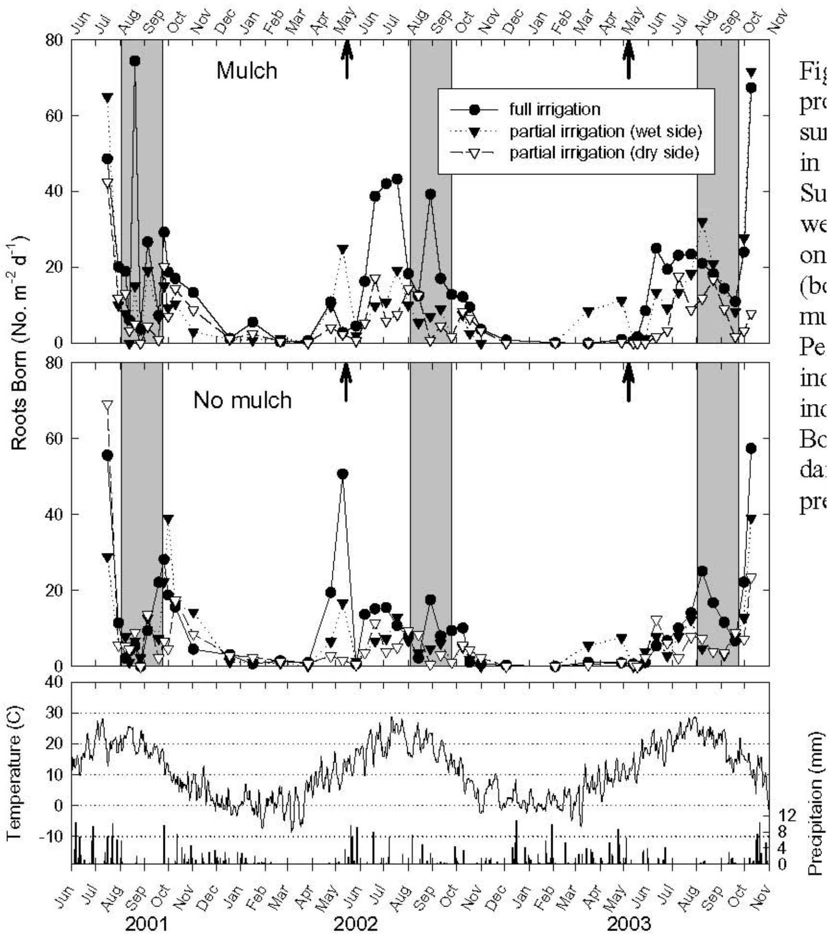

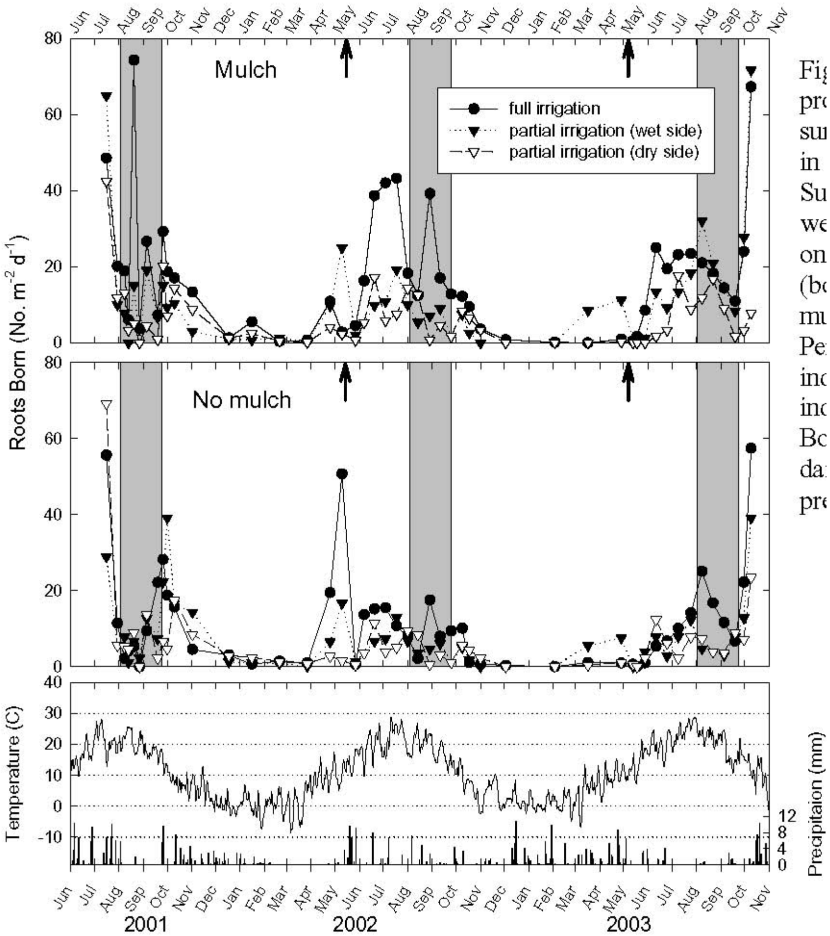

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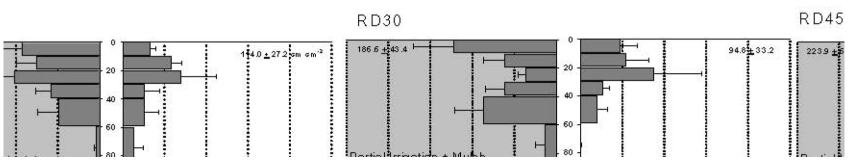

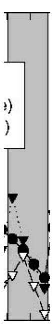

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Fig. 4. Patterns of daily root production per unit area of tube surface viewed over three seasons in a Gala/M9 planting in Summerland, BC. Treatments were partially irrigated (one-side only, 50% ET) and full irrigation (both sides, 100% ET) for mulched and unmulched trees. Period of deficit irrigation indicated by shading. Arrows indicate time of full bloom. Bottom graph indicates mean daily air temperature and precipitation at the site

Fig. 5. Gala/M9 vertical and horizontal root length distribution (+SE) determined at the end of the experiment. Horizontal root distribution was determined by collecting cores at radial distances (RD) of 15, 30 and 45 cm from the trunk in the row indicated by the three vertical panels. Vertical root distribution was determined at the following soil depths (cm): 0-20, 21-40, 41-60, 61-100, indicated by the stacked horizontal bars. Width of the bar is proportional to the depth interval sampled. Treatments were partially irrigated (1-side only, 50% ET) and fully irrigated (both sides, 100% ET) of mulched and unmulched trees. Shading indicates side of tree receiving irrigation. The partially irrigated treatments, consequently, are indicated by a wet (shaded) and dry (unshaded) panel. The fully irrigated treatment's left and right panels are identical.

Fig 6. Soil water content to a 40 cm depth in 2003 and 2004 (determined by TDR) in four irrigation treatments in a Golden Delicious/M9 orchard planted in sandy loam soil in Summerland, BC. The two control irrigation treatments were two emitters per tree (Both) either replacing the previous day's ET (100%) or water applied at 50% ET replacement. A. Treatment of partial irrigation where only one side of the tree is irrigated at 50% ET (one-side, Wet) and the other side is not irrigated (one-side, Dry). B. Partial root-zone drying treatment (PRD) where one side is either irrigated or allowed to dry in an alternating pattern *(Alternate 1 or 2)*.

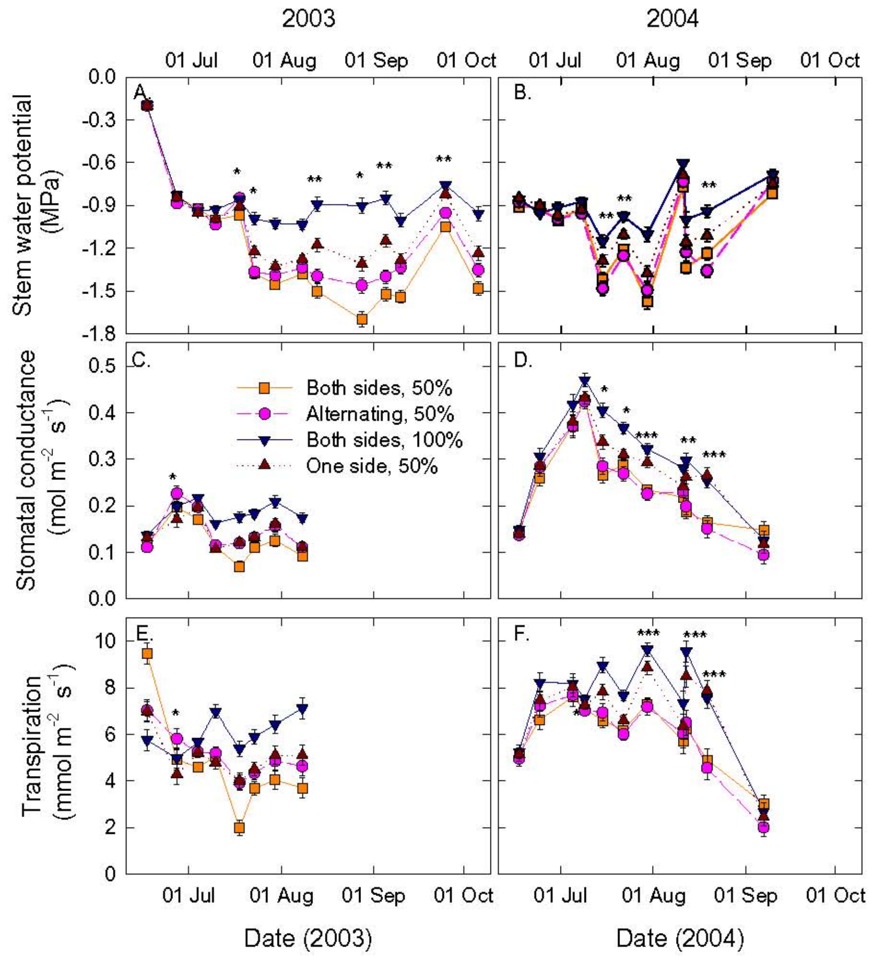

Fig. 7. Effects of partial and alternating irrigation (PRD) of Golden Delicious/M9 (+/- SE) on: A. & B. stem water potential, C & D. stomatal conductance and E & F. transpiration. Data were analyzed by repeated measures ANOVA. Significant difference between alternating and one-side irrigation indicated by asterisk. (* =*P*<0.05; ** = *P*<0.01; *** = *P*<0.001).

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Fig. 7. Effects of partial and alternating irrigation (PRD) of Golden Delicious/M9 (+/- SE) on: A. & B. stem water potential, C & D. stomatal conductance and E & F. transpiration. Data were analyzed by repeated measures ANOVA. Significant difference between alternating and one-side irrigation indicated by asterisk. (* =*P*<0.05; ** = *P*<0.01; *** = *P*<0.001).

Root production gives valuable information on carbohydrate allocation which may be at the expense of high allocation to fruit (Fig. 8). Root production was highest in the full irrigation (*Both-100%)* treatment in 2003 or 2004 in May and early June. During the first imposed drought period in 2003 (from July 16th to October 7th), highest root production was *Both-100%,* followed by *PRD*, *Both-50%*, *one-side Wet* and at the end of the season, *one-side Dry* treatment. In contrast, in 2004 (from June 18th to October 21st), trees in the *one-side Wet* treatment showed the highest root production followed by those in *PRD*, *Both-100%*, *Both-50%* and at the end *one-side Dry.* These data indicate how the established trees are adjusting their root systems to the change in irrigation in the experiment. Trees in the *PRD* treatment in 2004 exhibited little root growth in July and August but higher root growth in September and October.

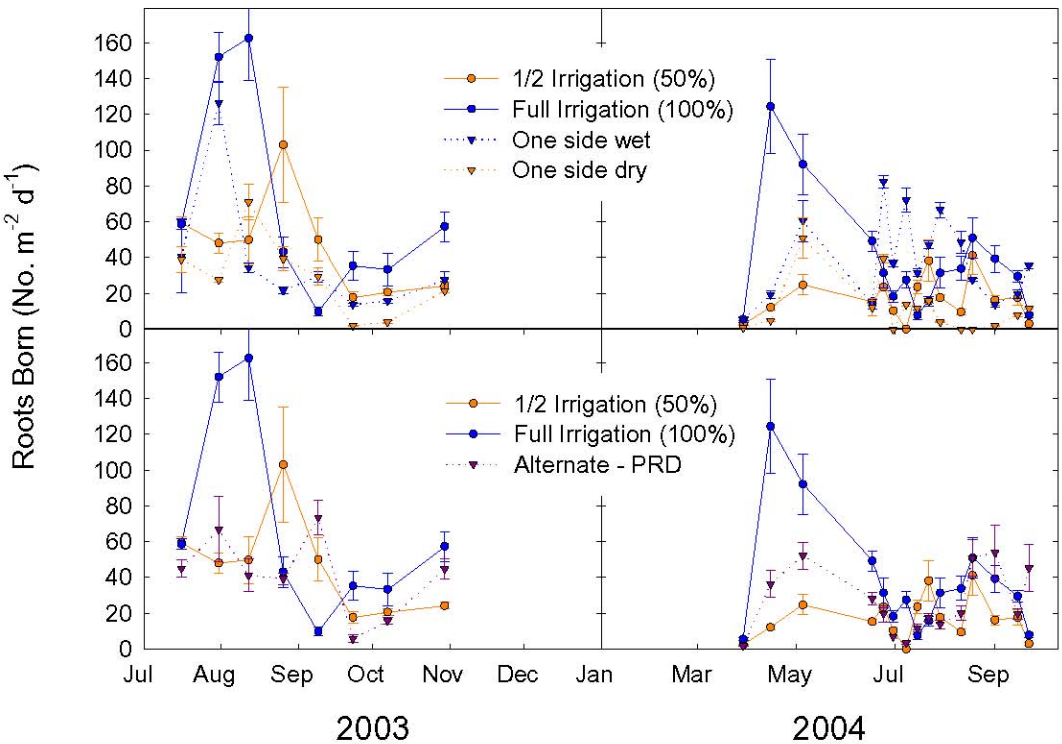

Fig 8. Root production in 2003 and 2004 (determined by number of roots per square meter per day, using minirhizotron tubes) in four irrigation treatments in a Golden Delicious/M9 orchard planted in sandy loam soil in Summerland, BC. The two control irrigation treatments had one minirhizotron per tree. A. Treatment of partial irrigation had two minirhizotron tubes per tree, one on the side of the tree that is irrigated at 50% ET (*one-side, Wet*) and another on the other side that is not irrigated (*one-side, Dry*). B. Partial root-zone drying treatment (*PRD*) had two minirhizotron tubes per tree, one in both sides of the tree, sides that are either irrigated or allowed to dry in an alternating pattern (*Alternate 1 or 2*).

A preliminary estimate of root mortality was calculated using the number of roots born on July 31, 2003, and the proportion of those roots that died by October 31, 2003 (Fig. 9). These results indicate that *one-side Dry* treatment had the highest mortality (60%) with more than 50% of the roots that were born in July, had died by October of the same year. Trees irrigated with the *Both-50%* treatment exhibited the second highest root mortality followed by *Both-100%* and lastly, *PRD.* These data are consistent with root mortality being partly a function of how much a group of roots are contributing to the overall water acquisition of the tree. More analyses of the data are planned.

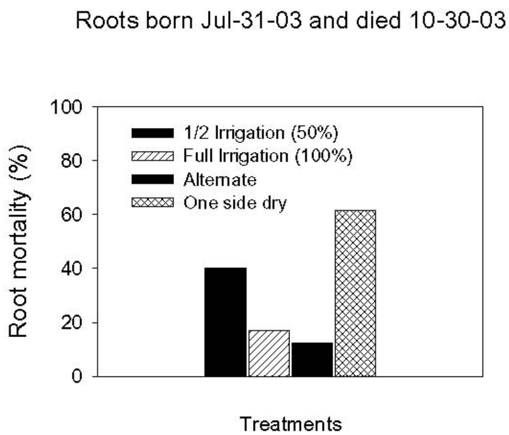

Table 1. Effects of four irrigation strategies on fruit yield, stem length growth and fruit quality in Golden Delicious/M9 trees in 2003 and 2004 (Summerland, BC, Canada). The irrigation treatments were: irrigating on both sides of a tree, on one side only or on alternating sides (partial root zone drying- PRD) at 50% or 100% previous day's ET. Stem length increase were calculated as a percentage of the stem length measured 25 June (just prior to initiating the irrigation treatments). Within a column, means followed by a different letter were significantly different at *P*<0.05 (Duncan's Multiple Range Test).

Treatment	***2003 harvest*** **Fruit No.**	**Yield/tree**	**Stem length**	***2004 harvest*** **Fruit No.**	**Yield/tree**	**Stem length**
	(Number/tree)	**(kg/tree)**	**(% incr.)**	**(Number/tree)**	**(kg/tree)**	**(% incr.)**
Both sides (100%)	52.3 a	8.74 a	121 a	230 a	15.0 ab	
Both sides (50%)	57.2 a	9.11 a	127 a	189 a	13.1 b	
One side (50%)	47.0 a	9.15 a	117 a	255 a	20.1 a	
Alternating (50%)	55.8 a	9.13 a	115 a	212 a	14.7 b	

Treatment	***Fruit size*** **(g/fruit)**	***Firmness N***	***Pressure*** **(lbs.)**	***Malic acid g/100ml***	***Soluble solids (%)***	***Sugar/ Acid***
2003 harvest						
Both sides (100%)	240 a	83.0 a	18.6 a	0.761 a	15.5 a	20.4 ab
Both sides (50%)	231 a	82.7 a	18.6 a	0.730 a	15.4 a	21.1 a
One side (50%)	239 a	80.0 a	18.0 a	0.769 a	14.9 a	19.4 b
Alternating (50%)	228 a	81.4 a	18.3 a	0.736 a	15.2 a	20.9 ab

2004 harvest						
Both sides (100%)	204 ab	72.4 ab	16.3 ab	0.495 a	12.0 b	24.4 a
Both sides (50%)	193 ab	75.0 ab	16.9 ab	0.513 a	12.7 a	24.9 a
One side (50%)	222 a	70.8 b	15.9 b	0.532 a	12.5 a	23.6 a
Alternating (50%)	180 b	76.1 a	17.1 a	0.503 a	12.7 a	25.3 a

Fig 9. Root mortality, determined by the roots that were born in July 31-03 and died by October 30-03. These results were significant at $P<0.001$ according to Chi-square analysis.

Stem growth, fruit yield or fruit quality were generally not affected by the type of irrigation in the first year of the study (Table 1). In 2004, fruit yield was highest in the *one-side* irrigation treatment and significantly lower in the *alternating (PRD)* and *Both sides (50%)* treatments. Stem length data in 2004 are still being analyzed. Fruit quality was also affected. Fruit size was significantly *larger* in the *one-side* only irrigation treatment than in the *alternating (PRD)* treatment, presumably because of the greater water stress in the *alternating* treatment (Fig. 7b). Fruit in the *alternating (PRD)* treatment, however, exhibited greater pressure readings and firmness than those in the *one-side* only treatment. Soluble solids and sugar/acid ratio did not differ between these two treatments. Since the improved fruit quality and yield in *PRD* occurred in the second year but not the first, it would be desirable to determine whether the 2004 results are confirmed in 2005.

Budget:

Project duration: 2002-2004 **Project total (3 years):** $112,065

Year	**Year 1 (2002)**	**Year 2 (2003)**	**Year 3 (2004)**
Total	35,388	38,350	38,327

Current year breakdown:

Item	**Year 1 (2002)**	**Year 2 (2003)**	**Year 3 (2004)**
Salaries			
Technical	28,188	26,150	32,627
Materials/Supplies/Travel	7,200	5,700	5,700
Equipment (Image capturing system)		6,500	
Total	35,388	38,350	38,327

MII match – This project was supported by matching investment initiative funds (MII, 50/50) provided through the Canadian government. These funds have been used to hire summer students, supplies and equipment.