Journal of the American Pomological Society 65(1): 42-53 2011

The Impact of Long-Term Evapotranspiration-Based Water Scheduling in Various Irrigation Regimes on Tree Growth, Yield, and Fruit Quality at Harvest in 'Fuji' Apple

ESMAEIL FALLAHI[1], BAHAR FALLAHI[2], BAHMAN SHAFII[3],
DENISE NEILSEN[4] AND GERRY H. NEILSEN[4]

Abstract

In a long-term study between 2002 and 2007, the use of crop evapotranspiration (ETc), when a precise crop coefficient value (Kc) was used, provided a reliable tool (irrigation scheduling) for determination of water requirement for 'Autumn Rose Fuji' apple (*Malus* × *domestica* Borkh). In this process, the crop coefficient was modified by percentage of ground shade (GS) and tree canopy maturity (M). Water use, tree growth, yield, and fruit quality attributes at harvest were examined under various irrigation systems that were scheduled using ETc. The average rainfall during the irrigation periods of 2004-2005, when trees were immature or at an early stage of maturity, was 66.0 mm, while during 2006-2007 irrigation periods, when trees were fully grown, it was 55.1 mm. Application of water through a drip system resulted in significantly lower water consumption as compared to applications through micro-jet sprinkler. When trees were mature, each tree with a micro-jet full sprinkler system (FS) received an average of 6461.7 L (994 mm) while each tree with a full drip system (FD) received 3996 L (614.1 mm) of irrigation water per growing season. Using a partial root zone drying regime through a micro-jet sprinkler system (PRS) reduced fruit size but slightly improved fruit color. In general, any deficit drip irrigation regime (65% of full-drip) initially increased yield due to induction of stress and the production of higher number of fruit spurs. However, production declined when the water-deficient treatment was repeatedly applied to the trees over several years. Application of water at 65% of full drip rate, applied on both sides of the tree row (DD), reduced fruit weight. However, when 65% of full drip rate was applied to only one of the alternating sides of the tree every other week (PRD), fruit was heavier than those with the DD treatment. Averaging values over all years indicated that fruit from trees with PRS had higher SSC and the difference was highly significant in 2004 when trees were young. However, trees with FS systems had slightly lower SSC when trees were mature (after 2005). Considering tree growth, yield, and quality attributes in this study, a well-calculated ETc-based full drip irrigation system (FD) is recommended over any other irrigation regime.

The constant increase in world population and decrease in irrigation water availability mandate a more efficient use of water in agriculture. Merging new orchard designs with more efficient irrigation systems can result in lower water consumption (11, 24, 26) while producing higher quality fruit (4, 5, 10, 11, 22, 25). The method of irrigation and injection of nutrients, particularly nitrogen (N) through water, affects water consumption and fruit quality in apples, which are critical issues in many parts of the world, including the Pacific northwestern region of North America (8, 11, 29).

Leib et al. (17) using a micro-jet sprinkler system, indicated that fruit size and yield of 'Fuji' apple in deficit irrigation (DI) were similar to those of partial root zone drying

[1] Professor and Director of Pomology Program, University of Idaho, Parma Research and Extension Center, 29603 U of I Lane, Parma, Idaho 83660, USA.
[2] Scientific Aide Senior in Pomology, University of Idaho, Parma Research and Extension Center, 29603 U of I Lane, Parma, Idaho 83660, USA.
[3] Professor and Director of Statistical Programs, University of Idaho, College of Agricultural and Life Sciences, Moscow, Idaho, 83844, USA
[4] Research Scientist, Pacific Agri-Food Research Centre, Agriculture and Agri-Food Canada, Summerland, B. C., Canada

irrigation (PRD) and conventional irrigation (CI) in the semi-arid climate of Washington State. Naor et al. (23) reported that yield and fruit size decreased as the rate of irrigation was reduced in 'Golden Delicious' apple in Israel. Previous reports have indicated that a reduction in water application may result in a reduction in apple firmness, relating this observation to the advanced maturity in fruits with water stress (7, 19). However, other researchers have shown that apples from non-irrigated plots were firmer than those from irrigated plots (2, 12, 13), perhaps because fruit from non-treated plots had smaller size (2).

Irrigation with a drip system uses less water than sprinkler irrigation (11, 34). However, irrigation through micro-jet sprinkler systems can improve the establishment and maintenance of orchard floor vegetation. Micro-jet sprinklers also create a cooler environment in the orchards under the fruit-growing conditions of Washington and Idaho (E. Fallahi, personal observation). Research has been conducted with orchard fertigation through drip systems in British Columbia (32, 37) and Europe (38). However, although there has been some progress in the understanding of micro-irrigation systems (6, 9, 27, 28, 30, 31), information on tree growth, yield and fruit quality for new apple cultivars under various regimes of drip or micro-jet sprinkler irrigation systems in the Pacific Northwest is lacking. Thus, the objective of this long-term experiment was to study the effect of five irrigation treatments consisting of two micro-jet sprinkler and three drip systems, using ETc-based water scheduling, on water use, tree growth, yield, and harvest-time fruit quality attributes of 'Autumn Rose Fuji'.

Materials and Methods

Orchard establishment. The experimental orchard was established at the University of Idaho Parma Research and Extension Center in spring and early summer of 2002. 'Autumn Rose Fuji' trees on RN 29 (Nic 29) rootstock (Columbia Basin Nursery, Quincy, WA) were planted at 1.52 x 4.27 m spacing with an east-west row orientation. 'Snow Drift' crab apple on RN 29 rootstock (C & O Nursery, Wenatchee, WA) was planted in each row as a pollinizer between every 10 'Autumn Rose Fuji' trees. The experimental site had a semi-arid climate, with an annual precipitation of about 297 mm and a sandy loam soil of pH ~ 7.3. Crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.], which is a drought tolerant grass, was planted as the orchard floor cover in all treatments.

Trees were trained into a vertical axis system during the dormant season in early March every year. Tree leaders were maintained at about 3.7 m height. Trees in all treatments were blossom-thinned at about 80% bloom with 5% lime sulfur, followed by one or two applications of post-bloom thinners. The first post-bloom thinner was a mixture of carbaryl (44.1% by weight a.i.; Sevin XLR; 1-naphthyl N-methylcarbamate; Bayer Crop Science; Research Triangle Park, NC) and Ethephon (21.7% a.i.; Ethrel [(2-chloroethyl) phosphonic acid]; Bayer Crop Science; Research Triangle Park, NC) each at a rate of 0.187% of formulation and was applied at petal-fall. The second post-bloom thinner (when applied, depending on the crop load) was carbaryl (Sevin XLR) at 0.125% to 0.187% formulation that was applied when fruitlet diameter was about 7 mm. Fruits were subsequently hand-thinned when fruits were about 18 mm in diameter (around mid-June) to maintain a space of at least 12.5 to 15 cm between fruits. Kaolin (95% a.i.; Surround; Englehard; Iselin, NJ) was sprayed for sunburn protection at the rate of 56.8 $kg{\cdot}ha^{-1}$ in early July, followed by three one-week interval applications, each at 28.4 $kg{\cdot}ha^{-1}$ every year.

Cultural practices other than irrigation were similar to those recommended for commercial orchards in the Pacific Northwest (36).

Irrigation regimes. We applied five irrigation regimes on each of the five experimental rows. A row of guard trees was used between every two experimental rows. These trees received only drip irrigation to prevent any possible over-spray from the sprinkler systems in the experimental rows. Trees from the guard rows were not used for any part of the study. The five irrigation regimes in this study were as follows:

1. Full Sprinklers (FS). 30-cm micro-jet sprinklers (Olson Ultra-jet, Santee, CA) were connected to a lateral polyethylene line installed in a 14-cm deep trench (subsurface), 30 cm away from and parallel to the tree row. Each micro-jet sprinkler was installed midway between two adjacent trees and covered a complete circle with a radius of 2.1 m. In this treatment, trees were irrigated once a week at the full rate of evapotranspiration (ETc) for apple starting in 2002 (see "Calculation for water application" below).

2. Partial Root-Zone Drying Sprinklers (PRS). Two 30-cm micro-jet sprinklers (the same brand as those in FS) were installed midway between two adjacent trees and fastened to two lateral polyethylene lines. Each of these sprinklers had a half-circle pattern (180^{o}) with a radius of 2.1 m and covered either the south or north side of the tree row. At each bi-weekly irrigation cycle, trees were irrigated only with sprinklers on one side and in the next bi-weekly cycle, they were irrigated by sprinklers on the opposite side. At each irrigation time, trees in this treatment received 50% of the FS treatment.

3. Full Drip (FD). One 16-mm drip line (Rain Bird Corporation, Azusa, CA) was installed in a 10-cm deep trench (subsurface), 30 cm away from and parallel to the tree row on each of the north and south sides of the tree row. Each of these lines was connected to a pressure regulator to keep the water pressure constant at 1.41 $kg \cdot cm^{-2}$. Pressure compensating emitters were spaced at 45 cm on each line, and each emitter delivered 2.27 $L \cdot hr^{-1}$ of water. Pressure compensation ensured consistent flow from each inline emitter throughout the entire length of tubing and the emitter design prevented debris from clogging emitters for maximum performance. The drip line on the north side of the tree was "off-centered" with the line in the south side to provide better water coverage. Trees in this system were irrigated twice a week at 100% of daily ETc (as described below), but adjusted for the ground shading area (GS). Therefore, in this treatment, liters of water applied per tree= (ETc in mm /percent drip efficiency factor) x 1.52 x 4.27 m spacing x %GS.

4. Deficit Drip (DD). This system was similar to the FD system, except that the amount of water applied in this system was 65% of that applied with FD during 2004-2007. This amount was applied to both sides of the trees at each application and frequency of application was the same as that of FD system.

5. Partial Root-Zone Drying Drip (PRD). With the exception of the frequency of irrigation, this system was identical to DD system. At each bi-weekly irrigation cycle, trees were only irrigated by one of these drip lines, and in the next cycle they were irrigated by the other line. This way, partial root-zone drying was created. In 2004 through 2007, the amount of water applied to this system was identical to that of DD system (65% of FD system).

Calculation for water application. Irrigation treatments were initiated in about mid-May and terminated in mid-October every year. Shortly before the first irrigation of the year, soil moisture was measured using AquaPro sensors (AquaPro Sensors, Decor, CA), and trees were watered to the soil saturation point. After this general irrigation, water requirements were calculated based on ETc where ETc= ETr x Kc with ETr (Penman-Monteith reference evapotranspiration) (1) being calculated from the Agri-Met Parma Weather Station data and Kc being the crop coefficient. Each year starting 2002, the crop water use coefficient was calculated as: Kc = K_c base + % M x (mature K_c – K_c base). Percent canopy maturity (%M) was a measurement of tree canopy size and was calculated as: % M = 3.05 + 2.558 x (%GS) – 0.016 x $(\%GS)^2$. Kc base was the base coefficient, calculated as the percentage area between the rows that was occupied by a cover crop. In this experiment, spacing between rows was 4.27 m and the herbicide strip extended 0.61

m on either side of the row. Thus, Kc base was [4.27-(0.61x2)]/4.27=0.71]. Percentage of ground shading (%GS) was estimated as the area of orchard shaded by the tree canopy at different stages of growth. Ground shading reached 62% and tree maturity reached 100% in early August, 2005. Thus, Kc values for mature trees were used after August 1, 2005. Since crested wheatgrass was planted as the orchard floor cover plant, value for mature Kc for each month was adopted from Proebsting (34) for apple with cover crop, i.e., 0.71 in May, 0.96 in June, 1.04 in July and August, 1.0 in September, and 0.79 in October.

Several random checks were made to test the accuracy of water delivery in various irrigation systems every year. Based on the precision in designing the irrigation systems and these random checks, an efficiency factor of 100% was assumed for all irrigation treatments. Rainfall during the growing seasons was generally low and when it rained, this amount was subtracted from the ETc value to calculate the actual amount of irrigation needed in each application.

Tree growth, yield and quality attributes. For monitoring tree growth, trunk cross sectional area (TCA) was calculated by measuring trunk diameter at approximately 20 cm above the bud union (about 12 cm above the soil line) in early March every year. For this purpose, two measurements were made, one from the east-west and the other one from the north-south directions and the diameter values were averaged and the radius (R) was computed. Tree TCA (cm^2) was calculated every year from 2004 through 2007. Yield per tree was recorded at harvest time and yield efficiency was calculated as (total yield per tree in kg)/TCA. Three individuals independently estimated fruit sunburn just before harvest, as percentage of fruit with visible sunburn symptoms on each tree, and the three values were averaged.

Twenty fruits were randomly sampled from each tree between October 17-20 during 2004-2007. For quality evaluation at harvest, fruits were gently wiped with a damp cloth and percentage of fruit with visible russet was recorded. Fruits were weighed and skin color was visually ranked on a scale of 1 to 5, with 1 = 20% red, progressively to 5 = 100% red. Soluble solids concentration (SSC) was measured using a temperature-compensated refractometer (Atago N1, Tokyo, Japan) and fruit firmness was measured, using an 11-mm probe, with a Fruit Texture Analyzer (Guss, Strand, Western Cape, South Africa). Fruit were cut equatorially in half and the number of fruit with visible water core symptoms was recorded. The percentage of water core was calculated as the percentage of water-cored fruits in the total number of fruit evaluated for quality. Starch degradation pattern (SDP) of equatorial slices of each fruit was recorded by comparison with the SDP standard chart developed for 'Fuji' apples by Bartram et al. (3).

Experimental designs and statistics. The experimental design was a randomized complete block with five irrigation treatments and five blocks (replicates). Each block contained 10 trees per plot of each irrigation treatment, 5 of which in the center of the plot were used for measurements (i.e., a total of 50 trees per treatment, of which 25 were used for measurements). Data were collected during 2004 through 2007. The assumption of normal data distribution was checked by computing univariate analyses for all tree responses in this study. Analyses of variance were conducted by using SAS (SAS Institute, Cary, NC, USA), with PROC GLM and means were compared by least significant difference (LSD) at $P \leq 0.05$.

Results and Discussion

There was no interaction between year and water treatment for any of the amount of applied water, tree growth, yield, or fruit quality attributes in this study. Thus, in addition to the results in each year, results of overall years from 2004 through 2007 are reported for each of these attributes.

Water application. The average precipitation during the irrigation periods of 2004-2005, when trees were not yet fully mature, was 66.0 mm (Table 1), and the average for

Table 1. Precipitation, cumulative evapotranspiration (ET), depth of applied water, and total volume of applied water per tree in 'Autumn Rose Fuji' with different irrigation regimes in 2004 and 2005.

	Monthly and cumulative precipitation, ET, and depth of applied water (mm) in 2004[y]								Monthly and cumulative precipitation, ET, and depth of applied water (mm) in 2005[y]									
Treat.[z]	May	June	July	Aug.	Sep.	Oct.	Cum.	Applied in 2004 (L/tree)	May	June	July	Aug.	Sep.	Oct.	Cum.	Applied in 2005 (L/tree)	Avg. cum. over 2004-05 (mm)	Applied over 2004-05 (L/tree)
Precip.	17.8	5.3	1.5	6.9	14.7	18.7	64.9		38.6	14.2	0.76	0	1.3	12.2	67.2		66.0	
ETr	145.0	212.1	235.2	191.8	94.7	46.9	925.7		104.1	192.3	259.8	248.4	133.1	18.5	956.2		941.0	
ETc	102.9	191.5	231.9	191.6	92.1	36.7	846.7		74.0	181.9	268.9	258.2	133.1	14.6	930.7		888.7	
FS	102.9	191.5	215.8	207.3	95.0	33.8	846.3	5399.8	70.1	163.8	249.9	274.7	129.0	10.4	898.2	5833.8	722.3	5616.8
PRS	83.8	95.8	107.9	103.6	47.5	16.8	455.4	2907.0	55.6	81.8	124.9	137.4	64.5	5.2	469.4	3048.1	452.4	2977.6
FD	36.3	72.9	107.9	85.1	47.4	19.8	369.4	2404.2	35.4	89.1	169.3	148.6	79.6	6.4	528.4	3438.0	448.9	2921.1
DD	32.3	47.2	70.1	55.4	31.2	12.8	249.0	1619.4	30.2	57.9	110.1	96.5	51.8	4.2	350.7	2281.5	299.9	1950.5
PRD	32.3	47.2	70.1	55.4	31.2	12.8	249.0	1619.4	30.2	57.9	110.1	96.5	51.8	4.2	350.7	2281.5	299.9	1950.5

[z] *Abbreviations:* Treat = Precipitation (Precip.), evapotranspiration or irrigation treatments; ETr = Penman Monteith evapotranspiration; ETc = Evapotranspiration coefficient for crop (apple); FS=Full Sprinklers (micro-jet); PRS=Partial Root-Zone Drying Sprinklers (micro-jet); FD= Full Drip; DD=Deficit Drip; PRD=Partial Root-Zone Drying Drip.

[y] Precipitation data covers the period of first irrigation (about mid-May) to last irrigations (about mid-October) in each year.

2006-2007 irrigation periods, when trees were mature, was 55.1 mm (Table 2). During the irrigation period in all years, July usually had the lowest precipitation. Water application in all irrigation regimes increased as trees matured (Tables 1 and 2). As expected, trees used the most water in July and August in all years. Trees with FS treatment received a significantly greater volume of water than those with drip systems every year. Trees with a FS system received 72% and 56% more water than those with a FD system in 2003 (data not shown) and 2004 (Table 1), respectively. The differences between water applications in FS and FD systems were consistent (38% to 41%) after 2005 (Table 2) because trees had reached the maximum ground shading (about 62%) and full canopy maturity after August 1, 2005. On average, mature trees with a FS system received 6461 L of water per tree (994 mm), while those with a FD system received 3996 L of water per tree (614 mm) over the 2006 and 2007 seasons (Table 2). Each tree with PRS received more water than those with any type of drip systems in 2004 and more than DD and PRD after 2004 (Tables 1 and 2). Although the volume of water applied to the trees with DD or PRD was only 65% of that applied to the trees with FD system, only minor water stress symptoms were observed in the trees with DD or PRD systems. The symptoms were somewhat more visible in the trees that received PRS irrigation. An obvious visible symptom was that trees receiving less than full levels of either micro-jet sprinkler or drip irrigations had smaller tree canopies and slightly earlier leaf senescence in late October.

Leib et al. (17) compared three micro-sprinkler irrigation systems in mature 'Fuji' trees in Washington State. In that study, the soil water content in the conventional irrigation (CI) was maintained close to field capacity, which was only 60-70% of estimated ETc for apple without cover crop. They estimated that irrigation scheduling based on soil-water measurements required 26% less water than what was predicted by the ETc model for an apple orchard without a cover crop. In that study, deficit irrigation (DI) and partial root zone drying (PRS) were at about 50% to 60% of the CI. They found that the 3-year average potential evapotranspira-

Table 2. Precipitation, cumulative evaportranspiration (ET), depth of applied water, and total volume of applied water per tree in ‘Autumn Rose Fuji’ with different irrigation regimes in 2006 and 2007.

Treat.[z]	Monthly and cumulative Precipitation, ET, and depth of applied water (mm) in 2006[y]							Applied in 2006 (L/tree)	Monthly and cumulative precipitation, ET, and depth of applied water (mm) in 2007[y]							Applied in 2007 (L/tree)	Avg. cum. over 2006-07 (mm)	Avg. applied over 2006-07 (L/tree)
	May	June	July	Aug.	Sep.	Oct.	Cum.		May	June	July	Aug.	Sep.	Oct.	Cum.			
Precip.	9.3	20.6	1.02	8.4	11.2	3.9	54.4		3.6	20.0	0	3.3	20.3	8.6	55.9		55.1	
ETr	145.1	208.0	302.5	204.7	137.2	70.4	1067.9		216.1	237.0	283.2	194.3	145.8	69.0	1145.4		1106.7	
ETc	103.0	199.6	314.5	212.9	137.2	55.6	1022.8		153.4	227.5	294.5	201.9	145.8	54.6	1077.7		1050.3	
FS	90.6	179.3	312.4	204.5	126.2	48.2	961.2	6249.9	152.3	190.4	312.8	201.6	123.7	45.9	1026.7	6673.5	994.0	6461.7
PRS	65.0	89.7	156.2	102.1	63.1	24.0	500.1	3253.6	99.4	95.0	156.4	100.8	61.8	22.9	536.3	3487.8	518.2	3370.7
FD	55.8	110.5	192.8	126.0	87.1	22.3	594.5	3872.0	94.0	138.5	170.2	124.4	87.9	18.6	633.6	4121.2	614.1	3996.6
DD	44.9	71.9	125.3	81.9	59.4	14.5	397.9	2572.4	71.1	90.0	110.6	80.0	57.1	12.1	420.9	2744.0	409.4	2658.2
PRD	44.9	71.9	125.3	81.9	59.4	14.5	397.9	2572.4	71.1	90.0	110.6	80.8	57.1	12.1	420.9	2744.0	409.4	2658.2

[z]Abbreviations: Treat.= Treatment; Precip.= Precipitation (Precip.), evapotranspiration, or irrigation treatments; ETr = Penman Monteith evapotranspiration; ETc = evapotranspiration for crop (apple); FS=Full Sprinklers (micro-jet); PRS=Partial Root-Zone Drying Sprinklers (micro-jet); FD= Full Drip; DD=Deficit Drip; PRD=Partial Root-Zone Drying Drip.

[y]Precipitation data covers the period of first irrigation (about mid-May) to last irrigations (about mid-October) in each year.

tion (ETo) was 991 mm, ETc was about 790 mm, and irrigation amounts applied were 707 mm, 570 mm, 511 mm for CI, DI, and PRS irrigation regimes, respectively. In our study when trees were mature (2006 and 2007), the 2-year average for ETr was 1106.6 mm and for ETc was 1050.3 mm (Table 2), and thus, these values were about 11% and 25% higher than similar measurements in Washington, respectively. During 2006 and 2007, we applied an average of 994 mm of water to the FS trees, which was about 287 mm (about 29%) higher than the levels applied to the CI treatment in Leib et al.’s report in Washington State (17). This difference is perhaps largely due the higher ETr and ETc values in Idaho than Washington. The difference could also be in part due to the fact that trees receiving FS were applied with water at full ETc level in our study (Table 2), while CI trees in their experiment received water at about 70% of ETc. Rainfall in both experiments was somewhat comparable.

Tree growth and yield. Trees with FS and FD irrigation always had higher TCA (Table 3) and more new shoots and foliage (data not shown) than those with other treatments across all years of the study. Trees with PRS consistently had smaller trees than those with other treatments every year, although differences were not always statistically significant. By 2007, these trees had significantly smaller TCA than any but the PRD treatment.

Trees with all drip systems tended to be more precocious and had higher yield per tree and yield efficiency than trees with FS system in 2003 (data not shown), 2004 and 2005 (Table 3). Water stress resulted in a higher production of fruiting spurs in trees with all drip treatments, particularly those with DD or PDR, leading to a higher production in early years (2003-2005). However, yield per tree in the DD treatment was significantly lower than those in FS in 2006 and 2007 because mature trees in the FS system had larger canopies. Average yield efficiency over 2004-2007 in trees with DD and PRD systems were significantly greater than those of FS and FD systems.

Since trees with a FD system received less water (Tables 1 and 2) and were more precocious

Table 3. Effects of different irrigation regimes on tree growth (trunk cross sectional area), yield per tree and yield efficiency of 'Autumn Rose Fuji' in 2004-2007.

Treat.[z]	Trunk cross sectional area (cm^2)				Yield (kg/tree)					Yield efficiency (kg/cm^2 of TCA)				
	2004[y]	2005	2006	2007	2004	2005	2006	2007	Cum. 2004-07	2004	2005	2006	2007	Avg. 2004-07
FS	17.1a	24.1 a	31.6 a	38.4 a	5.3 b	16.5 bc	20.4 a	22.2 a	64.4 ab	0.31 c	0.70 c	0.68 a	0.60 ab	0.58 c
PRS	12.3 b	17.1 b	22.0 b	25.9 c	8.9 ab	14.9 c	15.8 ab	18.8 ab	58.4 b	0.69 ab	0.89 bc	0.72 a	0.75 a	0.76 ab
FD	17.9 a	24.7 a	33.0 a	41.4 a	9.2 a	22.1 a	19.5 ab	20.3 ab	71.1 a	0.53 bc	0.94 abc	0.65 a	0.50 b	0.65 bc
DD	13.9 b	18.0 b	23.0 b	27.0 bc	9.6 a	20.7 ab	14.9 b	15.7 b	60.9 ab	0.71 ab	1.18 a	0.65 a	0.60 ab	0.78 a
PRD	13.2 b	19.5 b	24.9 b	30.7 b	11.0 a	19.8 abc	15.1 b	17.9 ab	63.8 ab	0.85 a	1.07 ab	0.63 a	0.59 ab	0.79 a

[z] Abbreviations: Treat.=Irrigation treatment: ETr = Penman Monteith evapotranspiration; ETc = Evapotranspiration for crop (apple); FS=Full Sprinklers (micro-jet); PRS=Partial Root-Zone Drying Sprinklers (micro-jet); FD= Full Drip; DD=Deficit Drip; PRD=Partial Root-Zone Drying Drip.

[y] Mean separation within columns by LSD at 5% level. Each value within each year represents the average of 5 blocks, each with 5 trees.

with significantly higher yield per tree than those with a FS system during 2004 and 2005 (Table 3), we suggest that FD is a preferred method of irrigation over a FS system for 'Fuji' apples as far as yield and water consumption factors are considered.

Leib et al. (17) reported that yield of 'Fuji' apple in DI and PRS systems were similar to those of conventional irrigation (CI) irrigation in Washington State. Lack of difference in their experiment is likely due to the fact that they had a shorter-term study and the irrigation volume applied in their control trees was only 60-70% of estimated ETc.

Fruit weight. Averaging values over 2004-2007 revealed that fruit from trees with FS and FD were significantly larger than those from all other treatments (Table 4). Fruit from trees receiving PRS and DD treatments were smaller than those from all other treatments every year and differences were significant when values were averaged over 2004-2007 (Table 4). This observation suggests that trees require irrigation at full ETc rates in order to produce larger fruits, and reduction of water application to 50% (as in PRS) and 65% (as in DD and PRD) of the ETc will result in fruit size reduction, which is particularly important for cultivars such as 'Gala' that are not inherently large. Location of the root zone wetting in drip system seems to influence fruit size, in that trees with PRD had larger average fruit size than those with DD irrigation over 2004-2007 (Table 4) although the volume of water applied was similar in these two treatments (Table 1 and 2). This result indicates that under a 65% deficit drip regime, it is more beneficial to apply the entire amount of water to an alternating side every other week than to both sides of the tree every week, because roots at greater depth will be irrigated with a PRD system but not a DD system. It is noteworthy that trees with PRD always had larger fruits than those with PRS (Table 4) although trees with PRD received 45%, 25%, 20%, and 22% less water than did trees with PRS in 2004, 2005, 2006, and 2007, respectively (Tables 1 and 2). This is because a wider but shallower area near the trees was irrigated and more water may have evaporated in the PRS system as compared to the PRD system.

In a study in the semi-arid climate of Washington State, fruit size of 'Fuji' apple in DI and PRS systems was similar to that of conventional irrigation (CI) irrigation (17), perhaps because the irrigation volume applied in their CI trees was only 60-70% of estimated ETc, in contrast to the present study. However, our results are in agreement with Naor et al. (23) who reported that yield and fruit size decreased as the rate of irrigation was reduced in 'Golden

Table 4. Effects of different irrigation regimes on average fruit weight, color, russet, and sunburn of 'Autumn Rose Fuji' in 2004-2007.

Treat.[z]	Fruit weight (g)					Fruit color (1-5 scale)[x]					Fruit russet	Fruit sunburn
	2004[y]	2005	2006	2007	Avg. 2004-07	2004	2005	2006	2007	Avg. 2004-07	Avg.2004-07 (%)[x]	Avg. 2004-07 (% of total yield)
FS	286 ab	301 a	309 a	303 a	300 a	3.5 a	3.5 ab	2.8 b	3.6 a	3.4 ab	37 a	11 b
PRS	236 c	256 c	268 b	254 b	254 c	3.6 a	3.9 a	3.1 ab	3.7 a	3.6 a	33 a	18 a
FD	287 a	295 a	315 a	298 a	299 a	3.4 ab	3.4 ab	3.3 a	3.8 a	3.5 ab	34 a	9 b
DD	270 b	275 b	265 b	251 b	265 c	3.0 b	3.5 ab	2.9 ab	3.5 a	3.2 b	25 b	19 a
PRD	277 ab	295 a	278 b	284 a	284 b	3.6 a	3.2 b	2.7 b	3.5 a	3.2 b	24 b	18 a

[z]Abbreviations: Treat.= Irrigation treatment: FS=Full Sprinklers (micro-jet); PRS=Partial Root-Zone Drying Sprinklers (micro-jet); FD= Full Drip; DD=Deficit Drip; PRD=Partial Root-Zone Drying Drip.

[y] Mean separation within columns by LSD at 5% level. Each value within each year represents the average of 5 blocks, each with 5 trees.

[x]Fruit skin color rating: scale of 1 to 5, with 1 = 20% red, progressively to 5 = 100% red. Percentage of fruit russet in each year = (number of fruit with russet in sampled fruits at harvest/total number of sampled fruit) x 100.

Delicious' apple in Israel.

Fruit color. Fruit color was not consistently affected by irrigation treatment (Table 4). However, averaging values over 2004-2007 period revealed that fruits from trees receiving the PRS treatment had slightly better (more uniform red) color than those from most other irrigation treatments, perhaps due to the presence of a less dense canopy (smaller TCA) in the PRS-treated tree (Table 3) and thus better light penetration, as reported by Lancaster (16). However, fruit from trees receiving DD and PRD tended to have slightly lower red color than fruit from other treatments (Table 4). Mills et al. (19) reported that DI increased skin red color in 'Braeburn' apple. In contrast, DI did not affect fruit color in 'Pink Lady' in Australia (33, 35). The contradictory impacts of deficit irrigation on fruit color could be due to differences between method of water delivery (drip vs. sprinkler), the prevailing temperatures at harvest for different places, cultivars, and/or volume of applied water in different deficit irrigation studies.

Fruit russet. Averaging over the period from 2004 to 2007, fruit from trees receiving DD and PRD had significantly less and those with PRS treatment had slightly (but not significantly) less russet than those with other irrigation treatments. A possible explanation is that these trees had smaller TCA and less dense foliage, so fruit do not get as much surface injury from the leaves during breezy or windy conditions, and thus have less russet. The lower fruit russet in these treatments may also have a physiological basis and this deserves further investigation.

Fruit sunburn. Fruit from trees treated with FS or FD systems had lower sunburn incidence than those from other treatments every year from 2004 through 2007 (data not shown) and the averages for this 4-year period are presented in Table 4. Trees from these two treatments had larger canopies and TCA (Table 3), and more foliage (data not shown); therefore, fruit had greater potential protection against direct radiation and predisposition to sunburn, which is a significant economic issue to growers.

Fruit soluble solids concentration. Averaging values over all years indicated that fruit from trees with PRS had higher SSC and the difference was

Table 5. Effects of different irrigation regimes on fruit soluble solids concentration, starch degradation pattern, firmness and water core of 'Autumn Rose Fuji' in 2004-2007.

Treat.[z]	Fruit soluble solids concentration (%)					Fruit starch degradation pattern (SDP rating)[x]					Fruit firmness	Fruit water core
	2004[y]	2005	2006	2007	Avg. 2004-07	2004	2005	2006	2007	Avg. 2004-07	Avg. 2004-07	Avg. 2004-07 (%)[x]
FS	15.3 b	15.5 b	15.4 c	15.4 b	15.4 d	3.3 b	3.5 b	3.3 b	4.3 a	3.6 b	7.9 a	52.5 b
PRS	16.6 a	15.9 a	16.1 a	15.7 b	16.1 a	3.5 ab	3.3 b	3.3 b	4.2 a	3.6 b	8.1 a	51.5 b
FD	15.1 b	16.0 a	15.9 ab	16.3 a	15.8 ab	3.6 ab	3.6 b	3.4 ab	4.0 a	3.7 b	8.0 a	65.4 a
DD	15.2 b	15.7 ab	16.2 a	15.8 ab	15.7 bc	3.6 ab	3.6 b	3.6 ab	4.3 a	3.7 b	8.0 a	50.2 b
PRD	15.0 b	15.6 ab	15.6 bc	15.9 ab	15.5 cd	3.8 a	3.9 a	3.8 a	4.3 a	4.0 a	8.0 a	51.2 b

[z] Abbreviations: Treat.=Irrigation Treatment; FS=Full Sprinklers (micro-jet); PRS=Partial Root-Zone Drying Sprinklers (micro-jet); FD= Full Drip; DD=Deficit Drip; PRD=Partial Root-Zone Drying Drip.

[y] Mean separation within columns by LSD at 5% level. Each value within each year represents the average of 5 blocks, each with 5 trees.

[x] Fruit starch degradation pattern (SDP): 1= lowest, progressively to 6=highest, using Bartram et al.'s chart (3). Water core percentage in each year = (number of fruit with water core in fruits sampled for quality analysis at harvest/total fruit sampled at harvest) x 100.

highly significant in 2004 when trees were young (Table 5), perhaps due to the smaller fruit size (Table 4). However, trees with FS systems had slightly lower SSC when trees were mature after 2005 (Table 3). In the present study, any treatment that received deficit irrigation (PRS, DD, PRD), had slightly higher concentrations of dry matter in the leaf when compared with full-irrigation treatments (FS and FD, data not shown). But these minor differences did not lead to an increase in the SSC of fruit from DD or PRD treatments, as has been implied in some previous research reports. Previous studies indicated that deficit irrigation increased SSC, including sucrose, glucose, fructose, and sorbitol in apple fruit, perhaps due to an increase in the concentration of dry matter (14, 19, 20, 21, 22). Leib et al. (17) showed that SSC in fruit from trees receiving DI was higher than in fruit from trees receiving CI. A two-year study by O´Connell and Goodwin (33) on 'Pink Lady' in Victoria, Australia, showed that SSC tended to be higher in DI fruit than CI fruit for each of the two years. In contrast, Talluto et al. (35) reported that 'Pink Lady' fruits from DI and CI treatments had similar SSC. Differences in the volume of water applied in deficit irrigation treatments and method of calculation for water requirement (ETc vs. soil moisture content) could partially explain these contradictory reports.

Starch degradation pattern. Averaging values over all years revealed that fruit from trees receiving PRD treatment had significantly higher SDP than those from other irrigation regimes (Table 5). Factors that lead to a greater hydrolysis of fruit starch can result in higher soluble solids concentrations in apples (15). However, a simple fruit dip in iodine solution (SDP) may not always be a reliable measure of the starch concentration of fruit. For example in our study in 2004, fruit from trees receiving PRD treatment had a significantly higher SDP than those from FS irrigation regime, while fruits in both treatments had a similar level of SSC (Table 5). This could be due to conversion of simple sugar to other metabolites.

Fruit firmness. Throughout this study, fruit firmness at harvest was unaffected by irrigation regime (Table 5). Some previous reports indicated that low water application reduced apple firmness, because of the advanced maturity in fruits with water stress in 'Golden Delicious' (7) and 'Braeburn' (19). However, other studies demonstrated that apples from non-irrigated plots were firmer than those from irrigated plots (2, 12, 13). Assaf et al. (2) indicated that fruit from trees subjected to water deficit were smaller than those from CI trees, which may account for the observed increase in fruit firmness. Leib et al. (17) observed that firmness of 'Fuji' apple was not affected by DI or PRS treatments as compared to CI, in five out of six different measurements during 2001-2003, which is in agreement with our results. Talluto et al. (35) showed that fruit firmness was not affected by DI treatment in 'Pink Lady' apple. These observations suggest that the impact of DI on apple fruit firmness may depend on the cultivar used in the study. Thus, a side-by-side study is required to reveal the potential cultivar-DI interactions.

Water core. Fruits from FD system always had higher water core (Table 5). Marlow and Loescher (18) and Mills et al. (19) reported that a high concentration of sorbitol will lead to the development of water core. Water core is not desirable in most apple cultivars while it is considered a positive quality attribute in certain markets for 'Fuji' . Thus, the presence of high water core in the fruits from FD treatment could be a positive aspect of this irrigation regime.

Conclusions. A significantly greater volume of water is required for trees under full micro-jet sprinkler systems than those with drip systems. However, application of water through a drip system, based on full ETc rate and adjusted by percentage of ground shade, can result in major water savings and often improves yield and fruit quality. Application of PRS reduces tree vigor and fruit weight while it may sometime improve fruit color and increase SDP. Fruit sunburn is reduced with application of water at full ETc rate in both sprinkler (FS) and drip (FD) systems because trees under these irrigation systems have a larger canopy and more foliage. Considering growth, yield, and fruit quality attributes in this study, a well-calculated ETc-based full drip irrigation system (FD) is recommended over any other irrigation regime for modern high-density apple orchards. 'Fuji' apple trees can be maintained with drip irrigation at 65% of drip ETc rate (i.e., 65% of FD) if certain fruit quality attributes are not of major concern for production. Application of water through a drip system at 65% of full drip ETc rate with the PRD system would be preferred over the DD regime if better fruit size at a reduced irrigation level was desired.

With an increasing demand for new cultivars, higher orchard tree density, and different canopy architectures, the impact of various irrigation systems and rates of water application on fruit quality and yield of apples needs to be further studied. Also, a concerted effort by various researchers is required to conduct an extensive study with a uniform set of cultivars and uniform protocol of irrigation over a wide range of climates to reveal the potential interactions between deficit irrigation and apple yield and quality.

Acknowledgements

The authors wish to thank the Idaho Apple Commission, International Fruit Tree Association, Washington Tree Fruit Research Commission, and the Idaho Agricultural Experiment Station for their financial support of this project. The authors are also thankful to the Columbia Basin, Van Well, and C & O Nurseries in Washington State for providing the experimental trees and to Mr. Richard L. Bronson, Pipeco, Fruitland, Idaho for his invaluable contribution and assistance in designing the irrigation layout and providing the irrigation materials for this project.

Literature Cited

1. Allen, R.G., L.S. Pereira, D. Raes and M. Smith. 1998. Crop evapotranspiration. guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.
2. Assaf, R., I. Levin and B. Bravdo. 1975. Effect of irrigation regimes on trunk and fruit growth rates, quality and yield. J. Hort. Sci. 50: 481-493.
3. Bartram. R.D., W. Bramlage, E.M. Kupferman, K.L. Olsen, M.E. Patterson and J. Thompson.

1993. Apple maturity program handbook. USDA–ARS Tree Fruit Research Station, Wenatchee, WA.

4. Behboudian, M.H. and T.M. Mills. 1997. Deficit irrigation in deciduous orchards. Hort. Rev. 21:105-131.

5. Behboudian, M.H., B.S. Mpelasoka, Z. Singh and T.M. Mills. 2005. Quality responses of deciduous fruits to deficit irrigation. Pp. 33-43. In: Dris, R. (ed.). Fruits: growth, nutrition, and quality. WFL Publisher (Science & Technology), Helsinki, Finland.

6. Chun, I. J., E. Fallahi, W. M. Colt, B. Shafii and R.R. Tripepi. 2001. Effects of rootstocks and microsprinkler fertigation on mineral concentrations, yield, and fruit color of 'BC-2 Fuji' apple. J. Amer. Pomol. Soc. 55:197-205.

7. Drake, S.R., E.L. Proebsting, M.O. Mahan and J.B. Thompson. 1981. Influence of trickle and sprinkle irrigation on 'Golden Delicious' apple quality. J. Amer. Soc. Hort. Sci. 106: 255-258.

8. Fallahi, E., W. M. Colt and B. Fallahi. 2001. Optimum ranges of leaf nitrogen for yield, fruit quality, and photosynthesis in 'BC-2 Fuji' Apple. J. Amer. Pomol. Soc. 55:68-75.

9. Fallahi, E., I. J. Chun, G. H. Neilsen and W. M. Colt. 2001. Effects of three rootstocks on photosynthesis, leaf mineral nutrition, and vegetative growth of 'BC-2 Fuji' apple trees. J. Plant Nutrition 24:827-834.

10. Fallahi, E., B. Fallahi, B. Shafii and B. Morales. 2007. Water use, tree growth, and leaf mineral nutrients of young 'Fuji' apples as influenced by different irrigation systems. Acta Hort. 721: 63-70.

11. Fallahi, E., R. Ratnaprabha, R. Tripepi, B. Shafii and B. Fallahi. 2007. Tree growth, yield, fruit quality, and mineral partitioning as affected by rootstock and irrigation methods. Inter. J. Fruit Science 7:3-24.

12 Guelfat'Reich, S., R. Assaf, B.A. Bravdo and I. Levin. 1974. The keeping quality of apples in storage as affected by different irrigation regimes. J. Hort. Sci. 49: 217-225.

13. Guelfat'Reich, S. and R. Ben-Arie. 1979. Effect of irrigation on fruit quality at harvest and during storage. Proc. XV Int. Congr. Refrig., Belgium. 3:423-427.

14. Kilili, A.W., M.H. Behboudian and T.M. Mills. 1996. Composition and quality of 'Braeburn' apples under reduced irrigation. Scientia Hort. 67:1-11.

15. Kramer, P.J. 1983. Water relations of plants. Academic Press, New York.

16. Lancaster, J.E. 1992. Regulation of skin color in apples. Crit. Rev. Plant Sci. 10: 487-502.

17. Leib, B.G., H.W. Caspari, C.A. Redulla, P.K. Andrews and J.J. Jabro. 2006. Partial root zone drying and deficit irrigation of 'Fuji' apples in a semi-arid climate. Irrig. Sci.: 85-99.

18. Marlow, G.C. and W.H. Loescher. 1984. Water core. Hort. Rev. 6:189-251.

19. 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.

20 Mpelasoka, B. S., M.H. Behboudian, J. Dixon, S.M. Neal and H.W. Caspari. 2000. Improvement of fruit quality and storage potential of 'Braeburn' apple through deficit irrigation. J. Hort. Sci. Biotech. 75:615-621.

21 Mpelasoka, B. S., M.H. Behboudian and S. Ganesh. 2001. Fruit quality attributes and their interrelationships of 'Braeburn' apple in response to deficit irrigation and to crop load. Gartenbauwissenschaft 66:247-253.

22. Naor, A. 2006. Irrigation scheduling and evaluation of tree water status in deciduous orchards. Hort. Rev. 32:111-165.

23. Naor, A., S. Naschitz, M. Peres and Y. Gal. 2008. Responses of apple fruit size to tree water status and crop load. Tree Physiol. 28:1255-1261.

24. Neilsen, D., G.H. Neilsen, D. Gregory, T. Forge and B.J. Zebarth. 2008. Drainage losses of water, N and P from micro-irrigation systems in a young, high density apple planting. Acta Hort. 792:483-490.

25. Neilsen, D., G.H. Neilsen, L. Herbert and S. Guak. 2010. Effect of irrigation and crop load management on fruit nutrition and quality for Ambrosia/M.9 apple. Acta Hort.(in press).

26. Neilsen, D., S. Smith, G. Frank, W. Koch, Y. Alila, W. Merritt, B.Taylor, M. Barton, J. Hall and S. Cohen. 2006. Potential impacts of climate change on water availability for crops in the Okanagan Basin, British Columbia. Can. J. Soil Sci. 86: 909-924.

27. Neilsen, G.H. and D. Neilsen. 2006. The effect of K-fertilization on apple fruit Ca concentration and quality. Acta Hort. 721:177-184.

28. Neilsen, G.H. and D. Neilsen. 2006. Response of high density apple orchards on course-textured soil to form of potassium applied by fertigation. Can. J. Soil Sci. 86:749-755.

29. Neilsen, G. H., D. Neilsen and L.C. Herbert. 2009. Nitrogen fertigation concentration and timing of application affect nitrogen nutrition, yield, firmness, and color of apples grown at high density. HortScience 44:1425–1431.

30. Neilsen, G. H., D. Neilsen, L.C. Herbert and E.J. Hogue. 2004. Response of apple to fertigation of N and K under conditions susceptible to the development of K deficiency. J. Amer. Soc. Hort. Sci. 129:26-31.

31. Neilsen, G. H., D. Neilsen, E. J. Hogue and L. C. Herbert. 2004. Zinc and boron nutrition management in fertigated high density apple orchards. Can. J. Plant Sci. 84:823-828.
32. Neilsen, G.H., P. Parchomchuck and D. Neilsen. 1994. Fertigation of fruit trees: the B.C. experience. Pp. 191-199. In: Peterson, A.B. and R.G. Stevens (eds.). Tree fruit nutrition. Good Fruit Grower, Yakima, Washington.
33. O´Connell, M.G. and I. Goodwin. 2007. Responses of 'Pink Lady' apple to deficit irrigation and partial root zone drying: physiology, growth, yield, and fruit quality. Austral. J. Agr. Res. 58: 1068-1076.
34. Proebsting, E. 1994. Strategy development for managing drought. Pp. 39-50. In: Williams K.M. and T.W. Ley (eds.). Tree fruit irrigation. Good Fruit Grower, Yakima, Washington.
35. Talluto, G., V. Farina, G. Volpe and R. Lo Bianco. 2008. Effects of partial root zone drying and rootstock vigor on growth and fruit quality of 'Pink Lady' apple trees in Mediterranean environments. Austral. J. Agr. Res. 59: 785-794.
36. Washington State University. 2009. Washington State University Tree Fruit Research and Extension Center. 4 July, 2009. Available at: http://www.tfrec.wsu.edu.
37. Yao, S., G.H. Neilsen and D. Neilsen. 2001. Effects of water stress on growth and mineral composition of 'Gala' apple fruit. Acta Hort. 564:449-456.
38. Zydlik, Z. and E. Pacholak. 2001. Fertigation effects on the concentration of mineral components in the soil and leaves, and the yield and quality of fruits in two apple tree cultivars. Acta Hort. 564:457-463.