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Leaf and Fruit Mineral Nutrient Partitioning Influenced by Various Irrigation Systems in 'Fuji' Apple over Four Years

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Abstract

Increasing water shortage crises, meshed with an increasing demand for newer cultivars, higher orchard density, and different canopy architectures mandates the study of the impact of various irrigation systems and rates of water application on tree growth, fruit quality, yield, and mineral partitioning. In a long-term study between 2004 and 2007, use of crop evapotranspiration (ETc), when a precise crop coefficient value (Kc) was used, provided a reliable tool (irrigation scheduling) for determination of the water requirement for 'Autumn Rose Fuji' apple (*Malus x domestica* Borkh). In this process, the crop coefficient was modified by percentage of ground shade (GS) and tree canopy maturity (M). Application of water at full ET rates through a full sprinkler (FS) or full drip (FD) system increased the size of tree canopy and leaf area and increased yield per tree and leaf K but reduced leaf Mg and Zn. Application of irrigation through a FS system decreased percentage of dry matter in the fruit but increased leaf Cu concentration and is potentially a preferred method for areas with Cu deficiency. Leaf Ca concentration in trees with a FS system was higher than those with a FD system but no significant differences were found among different irrigation systems in fruit Ca concentrations. A greater volume of water was delivered to trees under full-micro-jet sprinkler systems than those with drip systems. However, application of water through a drip system, calculated based on full ETc rate and adjusted for ground cover, resulted in major water saving and often improved yield.

Increasing world population and the decreasing availability of agricultural land and irrigation water require higher levels of production from each unit of land and water in order to meet demand.

Tree canopy size in high-density orchards may be limited by rootstock (Fallahi et al., 2007, 2013), by training and/or by pruning (Hampson et al., 2002; Sansavini et al., 1986), or by deficit irrigation (Ebel et al., 1995; Marsal et al., 2001; Talluto et al., 2008; O'Connel and Goodwin, 2007; Yao et al, 2001).

Combining new orchard designs with more efficient irrigation systems and improved rootstocks can result in lower water consumption (Fallahi et al., 2007), while simultaneously producing higher quality fruit (Behboudian et al., 2005; Drake et al., 1981; Fallahi et al., 2007; Neilsen et al., 2010). Irrigation with a drip system uses less water than sprinkler irrigation (Fallahi et al., 2013; Proebsting, 1994, Neilsen et al., 1994). However, irrigation through micro-jet sprinkler systems can improve the establishment and maintenance of orchard floor vegetation which is important for sustainable fruit production in the mid-west of the USA. Micro-jet sprinklers also create a cooler environment in the orchards under fruit-growing

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conditions of Washington and Idaho (personal information).

Leib et al. (2006) indicated that fruit size and yield of 'Fuji' apple in deficit irrigation (DI) were similar to those of partial root zone drying irrigation (PRD) and conventional irrigation (CI) in the semi-arid climate of Washington State. Naor et al. (2008) reported that yield and fruit size decreased as the rate of irrigation was reduced in 'Golden Delicious' apple in Israel. Previous reports indicated that a reduction in water application might advance fruit maturity and thus reduce firmness in apples (Drake et al., 1981; Mills et al., 1994).

Neilsen et al. (1995) reported that 'Gala' apple trees irrigated using a micro-jet irrigation system had higher leaf P, K, and Cu, but lower leaf N, Mg, and Mn concentrations than trees irrigated with a drip system. Rootstocks also have a major impact on leaf and fruit nutrient concentrations in apples (Chun et al., 2001; Fallahi et al., 1985a, b, c, 2001a, b, 2007; Neilsen and Hampson, 2014). Although there has been some progress in understanding the impact of micro-irrigation systems (Chun et al., 2001; Fallahi et al., 2007; Neilsen et al., 1995, 2010), information is lacking on the impact of irrigation methods on tree performance and leaf and fruit mineral nutrient concentrations in new apple cultivars in the US Pacific Northwest. The objective of this long-term (4-year) experiment was, therefore, to study the effects of two irrigation methods consisting of two micro-jet sprinklers or a three drip system, using ETc-based water scheduling, on tree growth, leaf size, and leaf and fruit mineral nutrient concentrations between 2004 and 2007.

Materials and Methods

Orchard establishment and general cultural practices. The experimental orchard was established at the Parma Research and Extension Centre, University of Idaho in the spring and early-summer 2002. 'Autumn Rose Fuji' trees on M.9RN 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. All trees were trained to a vertical axis system during the dormant season in early-March each year. All tree leaders were maintained at approx. 3.55 m in height. The experimental site was located at 43.7853° N, 116.9422° W, and had a semi-arid climate with an annual precipitation of approx. 297 mm on a sandy loam soil of approx. pH 7.3.

Crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.), a drought-tolerant grass, was planted as the orchard floor cover in all treatments. Trees in all treatments were blossom-thinned at approx. 85% full bloom with 5% (v/v) lime sulphur, followed by one or two applications of post-bloom thinners, as described by Fallahi et al. (2011). Weeds were controlled by three applications of Roundup® herbicide (glyphosate) during early and middle of each growing season to maintain a 1.22 m-wide weed strip under the trees.

The nutrients applied to the experimental trees from 2002 - 2007 are listed in Table 1. Nitrogen as UAN 32 (urea and ammonium nitrate, 32% N) was applied at the total annual rate of 60 g N/tree via fertigation twice each year (Table 1). The first N was applied at the rate of 30 g/tree in late-May and the second one was applied at the same rate two weeks after the first application each year. Potassium (when used) was applied as potassium hydroxide, containing 13% K_2O, via fertigation, once a year in late-May. Phosphorous, as monoammonium phosphate (61% P_2O_5), was applied at the rate of 150 g of formulation to each tree-planting hole, only once at the time of planting (Table 1). Calcium and micronutrients, particularly, Fe and Zn, were sprayed twice in spring and once in early summer each year (Table 1). Cultural practices, other than irrigation, were similar to those recommended for commercial orchards in the Pacific Northwest of the USA (Washington

Table 1. Application and frequency of nutrient materials applied to 'Autumn Rose Fuji' apple trees during 2002-07.[z]

Year	N (UAN 32, 0.43 kg N/L)	P ($NH_4H_2PO_4$)	K (Potassium hydroxide, 13% K_2O)	Ca (Metalosate Calcium, 6% Ca)	B (Metalosate Boron, 5% B)	Fe (Metalosate Iron, 4% Fe)	Zn (Metalosate Zinc, 6.8% Zn
2002	72 L ha^{-1}/time	150g/ tree, at planting only	None	3 times, 2 L ha^{-1}/time	Once, at 1.5 L ha^{-1}	3 times, 2.92 L ha^{-1}/time	3 times, 2.92 L ha^{-1}/time
2003	108 L ha^{-1}/time	None	None	3 times, 2 L ha^{-1}/time	Once, at 1.5 L ha^{-1}	3 times, 2.92 L ha^{-1}/time	3 times, 2.92 L ha^{-1}/time
2004	81 L ha^{-1}/time	None	None	3 times, 2 L ha^{-1}/time	Once, at 1.5 L ha^{-1}	3 times, 2.92 L ha^{-1}/time	3 times, 2.92 L ha^{-1}/time
2005	108 L ha^{-1}/time	None	Once, 377 L ha^{-1}	3 times, 2 L ha^{-1}/time	Once, at 1.5 L ha^{-1}	3 times, 2.92 L ha^{-1}/time	3 times, 2.92 L ha^{-1}/time
2006	108 L ha^{-1}/time	None	None	3 times, 2 L ha^{-1}/time	Once, at 1.5 L ha^{-1}	3 times, 2.92 L ha^{-1}/time	3 times, 2.92 L ha^{-1}/time
2007	108 L ha^{-1}/time	None	Once, 377 L ha^{-1}	3 times, 2 L ha^{-1}/time	Once, at 1.5 L ha^{-1}	3 times, 2.92 L ha^{-1}/time	3 times, 2.92 L ha^{-1}/time

[z] UAN 32 and potassium hydroxide were used through fertigation in June, $NH_4H_2PO_4$ was applied as dry material by hand at planing, and Metalosate materials were sprayed to the tree canopy from early to mid-growing season, according to the frequency in the table every year.

State University, 2015).

The experimental design was a radomised-complete-block with five irrigation methods as treatments and five blocks (replications) with nine trees per block.

Tree size, yield, leaf size, and leaf and fruit mineral nutrient concentrations. To measure tree growth, trunk cross sectional area (TCA) values were calculated by measuring trunk diameters, approx. 20 cm above the bud union, in early-March each year from 2004 to 2007. Because of the presence of strong positive relationships between tree vigour and TCA, and between TCA and the degree of tree dwarfism (Fallahi et al., 2002), TCA is used as a measure of tree growth throughout this article. Fruit yields per tree were recorded between October 20 and 25 each year. Twenty fruit were sampled at random from each tree at harvest. Ten of these fruit were used to measure fruit quality attributes (i.e., fruit size, color, firmness, skin russet, soluble solids concentration, starch degradation pattern, and water core at harvest and results were published in an earlier report (Fallahi et al., 2011). These fruits were washed (as described for leaves later), cut equatorially and 10 pieces were taken from each fruit in each composite sample.

Leaf areas (LA), fresh weights (FW), dry weights (DW), and ion concentrations were measured and dry weight percentages (DW%) were calculated as (DW/FW) × 100 each year. To measure LA, FW, DW, and ion concentrations, 30 leaves were sampled per tree at random from the middle of current-season shoots in mid-August each year. Leaf areas were measured using a Li-Cor Leaf Area Meter (Model LI-3100; Li-Cor Co., Lincoln, NE, USA). Leaves and fruits were washed in 1% (v/v) Liqui-Nox anionic detergent (AlcoNox Inc., White Plains, NY, USA), rinsed in three different plastic containers, each containing 25 L of distilled water, and dried in a forced-air oven at 65°C. The dried leaf and fruit tissues were ground to pass a 40-mesh screen using a Cyclotec Sample Mill (Model 1093; Tecator, Hoganas, Sweden).

Nitrogen (N) concentrations were determined by combusting the dry leaf and fruit tissues using a LECO Protein/Nitrogen Analyser (Model FP-528; LECO Corp., St. Joseph, MI, USA). The dry leaf and fruit tissues were analysed for potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) by dry-ashing at 500°C, digestion with 10% (v/v) nitric acid, and atomic absorption spectrophotometry (Perkin-Elmer B1100; Norwalk, CT, USA).

Irrigation treatments. The method for ETc calculation and the design of the irrigation systems were described in an earlier related publication (Fallahi et al., 2011) but a brief description of the five irrigation methods is as follows:

1. Full Sprinklers (FS). In this system, a 30-cm micro-jet sprinkler (Olson Ultra-jet, Santee, California, USA) was connected to a lateral polyethylene line. Each micro-jet sprinkler was installed mid-way 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 apples from 2002 onwards.
2. Partial Root-Zone Drying Sprinklers (PRS). In this system, two 30-cm micro-jet sprinkler (the same brand as those in FS) were installed mid-way between two adjacent trees and fastened to two lateral polyethylene lines. Each of these sprinklers had a half-circle pattern (180°) 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 other side. At each irrigation time, trees in this treatment receive 50% of the FS treatment.
3. Full Drip (FD). In this system, one 16-mm drip line (Rain Bird Corporation, Azusa, CA) was installed in a 10-cm trench (subsurface), 30 cm away from and parallel to the tree row at each of the north and south sides of the tree row. Trees in this system were irrigated twice a week at 100% of daily ETc (as described later in the "Calculation of water use" section, 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 to FD during 2004-2007. This amount was applied to both sides of the trees at each application and frequency of application was similar to that of the FD system.
5. Partial Root-Zone Drying Drip (PRD). With exception to the frequency of irrigation, this system was identical to the DD system. At each bi-weekly irrigation cycle, trees were only irrigated by one of these drip lines, and in the next cycle the other line was used. This way, partial root-zone drying was created. In 2004 through 2007, the amount of water applied by this system was identical to that of the DD system (65% of the FD system).

Irrigation started in about mid-May and ended in mid-October every year. Water requirements were calculated based on ETc where ETc = ETr x Kc. In this equation, ETr (Penman-Monteith reference evapotranspiration) (Allen et al., 1998) was calculated from the Agri-Met Parma Weather Station data and Kc was the crop coefficient. Each year starting in 2002, the crop water use coefficient was calculated as:

$Kc = K_c \text{ base} + \% M \times (\text{mature } K_c - K_c \text{ base})$.

Percent canopy maturity (%M) was a measurement of canopy size and was calculated as: $\%M = 3.05 + 2.558 \times (\%GS) - 0.016 \times (\%GS)^2$.

Kc base was the base coefficient, calculated as the percentage area between the rows that was occupied by a cover crop. In our 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 at midday by the tree canopy at different stages of growth. Ground shading reached 61.76% and tree maturity reached 100% on August 1, 2005. Thus, Kc values for mature trees were used after August 1, 2005. Since crested wheatgrass was planted as the orchard floor cover plant, the value for mature Kc for each month was adopted from Proebsting (1994) for apples with a cover crop, i.e., 0.71 in May, 0.96 in June, 1.04 in

Table 2. Effect of various irrigation regimes on trunk cross sectional (TCA) area in 2007, yield, leaf fresh and dry weights, leaf area, and leaf and fruit percent dry weights in 'Autumn Rose Fuji' during 2004-2007.

Irrigation[z]	2007 TCA (cm^2)	2004-07 cumulative yield (kg/tree)	2004-07 average: Leaf fresh weight (mg/leaf)	Leaf dry weight (mg/leaf)	Leaf percent dry weight	Leaf area (cm^2/leaf)	Fruit percent dry weight
FS	38.4 a[y]	64.4 ab	826 a	330 a	40.0 b	29.4 a	17.6 c
PRS	25.9 c	58.4 b	760 b	316 ab	41.5 a	27.7 b	18.6 a
FD	41.4 a	71.1 a	808 a	322 ab	39.9 b	28.6 a	18.6 a
DD	27.0 bc	60.9 ab	760 b	313 b	41.2 ab	27.4 b	18.3 ab
PRD	30.7 b	63.8 ab	799 a	322 ab	40.3 ab	28.3 ab	17.8 bc

[z] Abbreviations: 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 five blocks, each with five trees.

July and August, 1.0 in September, and 0.79 in October. Rainfall during the growing seasons was generally small and, when it rained, this amount was subtracted from the ETc value to calculate the actual amount of irrigation needed in each application.

Results and Discussion

Tree growth and yield. Trees with FS and FD irrigation had higher TCA (Table 2) and longer new shoots and greater foliage (data not shown) than those in the other treatments over the 2004-2007 period.

Trees with all drip systems tended to be more precocious and had higher yield per tree than those with a FS system during 2004 (data not shown). Cumulative yields of trees with the FD treatment over the 2004-2007 period were significantly greater than those of trees with PRS treatment (Table 2). Since trees with a FD received less water while being more precocious and tended to have higher cumulative yield than those with a FS system (Fallahi et al., 2011), we suggest that FD is a preferred method of irrigation over other irrigation systems for 'Fuji' apples as far as yield and water consumption factors are considered.

Leib et al. (2006) reported that yield of 'Fuji' apple in DI and PRS systems were similar to those of conventional irrigation (CI) in Washington State. Lack of a 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.

Leaf growth and weight, and fruit dry weight. Averaging values over 2004-2007 revealed that leaves from trees with a FS system had significantly higher fresh weight and larger areas but lower percent dry weight than did those with a PRS system (Table 2). Overall, leaves from trees with FS and FD systems had significantly larger area (leaf area) than those with PRS or DD systems (Table 2). Application of irrigation through a FS system decreased percentage of dry matter in the fruit tissue. These results suggest that leaves and fruit from trees with the FS system had higher water content because they received a higher volume of water.

Leaf and fruit macronutrients. Trees under the FD irrigation system had lower leaf nitrogen (N) than those under other drip or sprinkler irrigation treatments in each year, although differences were not always significant. These differences became more significant when values were averaged over all years (Table 3). Both volume and placement of applied water should have had a direct effect on the concentrations of leaf N in this study. Trees in all irrigation treatments received the same amount of N fertilizer through fertigation. A possible reason for the lower leaf N in the FD treatment, as compared to the other drip systems, was due to the creation of a dilution effect, because trees in FD system had larger canopies and tended to have more yield (Table 2) and larger fruits (Fallahi et al., 2011). Another possible explanation is that trees in FD received a higher volume of water than did those with other drip systems (DD and PRD). Trees in all drip systems received the same rate of N fertilizer in two splits and were irrigated twice weekly, but the higher volume of water in the FD system could have shifted a portion of N away from the root zone. If the second possibility was one of the reasons for the lower leaf N in trees with FD treatments, we could have gained better N uptake efficiency if we had applied the same rate of annual N in three or four splits rather than two, and this needs further investigation. The lower average leaf N over all years in the trees with a FD system as compared to those with a FS system was because roots of trees under the FS system were spread in a wider area and thus intercepted more N. The differences between leaf N concentrations in FS and FD systems were not significant in 2004 and 2005 (Table 3) because a portion of fertigated N fertilizer was outside of the distribution of roots when trees were young. However, these differences became statistically significant in 2005 and 2006 when trees matured and roots were further expanded and able to utilize the fertigated N more efficiently.

Fruit in trees of all irrigation treatments had lower N concentrations when trees were young in 2004 and 2005 compared to mature trees in 2006 and 2007 (Table 3). The reason could be that trees were growing at a faster rate and had a lower crop when they were young and thus, more N was distributed to the new foliage. When trees matured and canopy was established, there was more N partitioning in the fruit. Trees under the PRD system often tended to have higher fruit N than those with other irrigation systems, and the physiological reason for this is not clear. However, fruit from the PRD treatment also had a higher starch degradation pattern (SDP) (Fallahi et al., 2011), and fruit N and SDP can be interrelated. Fruits with higher N were shown to produce more ethylene and mature faster than those with lower N (Fallahi et al., 1985b). Since advanced SDP is one of the indicators for advanced maturity, higher fruit N could have induced the advanced maturity of fruit in the PRD system.

Leaf K concentrations in trees with full irrigation regimes (FS and FD) were greater than those with deficit or partial irrigation systems every year (Table 4). Also, trees with FD often had lower leaf K than those with FS system, and these differences were statistically significant in two out of four years. These differences were more pronounced when values were averaged over four years. This observation underscores the needs for considering many orchard and cultural practices when interpreting results of leaf analyses. In this case, irrigation treatment alone created wide differences in the leaf K concentrations while all other cultural practices, including quantity of K applied, was the same in all treatments. For example, in the 2005 data, it could be concluded that trees under a FS system with a leaf K value of 1.61% were in a sufficient range while those under partial or deficit irrigations were

Table 3. Effect of various irrigation regimes on leaf and fruit nitrogen (N) in 'Autumn Rose Fuji' during 2004-2007.

	Leaf N (% DWt)					Fruit N (% DWt)				
Irrigation[z]	2004	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07
FS	1.95 b[y]	2.28 ab	2.33 a	2.18 a	2.18 a	0.15 a	0.12 b	0.29 a	0.22 b	0.19 b
PRS	2.16 a	2.25 ab	2.21 b	2.12 ab	2.18 a	0.13 a	0.14 ab	0.24 bc	0.25 ab	0.18 b
FD	1.99 b	2.22 b	2.14 b	2.07 b	2.11 b	0.15 a	0.12 b	0.23 c	0.23 ab	0.18 b
DD	2.11 a	2.31 a	2.17 b	2.15 ab	2.19 a	0.16 a	0.12 b	0.24 bc	0.22 b	0.18 b
PRD	2.12 a	2.31 a	2.19 b	2.16 a	2.19 a	0.16 a	0.22 a	0.28 ab	0.27 a	0.23 a

[z] Abbreviations: 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 five blocks, each with five trees.

Table 4. Effect of various irrigation regimes on leaf and fruit potassium (K) and magnesium (Mg) concentration in 'Autumn Rose Fuji' during 2004-2007.

Irrigation[z]	Leaf K (% DWt)					Fruit K (% DWt)					Leaf Mg (% DWt)					Fruit Mg (ppm)
	2004	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07	Ave. 2004-07
FS	1.56 a [y]	1.61 a	1.45 a	1.42 a	1.51 a	0.87 a	0.84 a	0.76 a	0.76 a	0.81 a	0.29 d	0.34 c	0.35 b	0.37 a	0.34 b	269 a
PRS	1.27 bc	1.30 cd	1.33 b	1.32 a	1.31 c	0.73 b	0.81 ab	0.65 b	0.81 a	0.76 a	0.39 ab	0.41 a	0.38 a	0.38 a	0.39 a	254 a
FD	1.34 b	1.48 b	1.43 ab	1.43 a	1.42 b	0.81 ab	0.77 b	0.73 ab	0.72 a	0.76 a	0.34 c	0.34 c	0.32 c	0.31 b	0.33 b	240 a
DD	1.22 c	1.22 d	1.20 c	1.33 a	1.25 c	0.79 ab	0.75 b	0.70 ab	0.84 a	0.77 a	0.36 bc	0.39 ab	0.38 a	0.37 a	0.37 a	272 a
PRD	1.18 c	1.37 c	1.34 ab	1.40 a	1.32 c	0.78 b	0.78 ab	0.69 ab	0.78 a	0.77 a	0.40 a	0.38 b	0.37 ab	0.39 a	0.39 a	251 a

[z] Abbreviations: 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 five blocks, each with five trees.

Table 5. Effect of various irrigation regimes on leaf and fruit calcium (Ca) and iron (Fe) concentrations in 'Autumn Rose Fuji' during 2004-2007.

Irrigation[z]	Leaf Ca (%)					Fruit Ca (ppm)					Leaf Fe (ppm)					Fruit Fe (ppm)
	2004	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07	Ave. 2004-07
FS	1.52 b [y]	1.90 a	1.86 a	1.87 a	1.78 a	153 ab	220 a	180 a	145 b	175 a	52 bc	59 ab	74 b	67 a	63 b	4.91 a
PRS	1.60 b	1.65 c	1.75 b	1.77 b	1.69 bc	132 b	204 a	121 b	188 a	165 a	57 a	61 a	83 a	66 a	67 a	4.86 a
FD	1.51 b	1.75 bc	1.75 b	1.66 c	1.67 c	147 ab	202 a	175 a	130 b	163 a	50 c	56 b	69 b	63 a	59 c	4.70 a
DD	1.55 b	1.69 bc	1.60 c	1.67 c	1.63 c	161 a	196 a	194 a	183 a	177 a	53 abc	61 a	69 b	62 a	61 bc	4.75 a
PRD	1.84 a	1.77 b	1.72 b	1.66 c	1.75 ab	150 ab	205 a	157 ab	140 b	165 a	55 ab	59 ab	74 b	62 a	62 bc	4.95 a

[z] Abbreviations: 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 five blocks, each with five trees.

deficient according to leaf threshold guides (Shear and Faust, 1980). Then to alleviate the K deficiency, extra application of K fertilizer could be recommended while, in fact, this deficiency could be eliminated by application of additional water. Fruit K was not consistently affected by irrigation treatments (Table 4).

Trees that received full irrigation systems had lower leaf Mg concentration than did those with deficit or partial irrigation systems (Table 4). Thus, leaves from trees with PRS, DD or PRD systems had greater leaf Mg concentrations than did those from other treatments every year, although differences were not always significant. These differences were more pronounced when values were averaged over four years. This pattern is opposite to the situation that we observed for leaf K as described above, which confirms the presence of antagonistic effects between the uptake and translocation of K and Mg (Fallahi and Simons, 1993). Fruit Mg was not affected by irrigation treatment within each year (data not shown) or when values were averaged over four years (Table 4).

There was no consistent pattern in the effects of irrigation system on the leaf or fruit Ca concentrations, although leaf Ca tended to be higher in the FS treatment in three of four years of this study (Table 5). Lack of any significant difference in the firmness of fruits from different irrigation systems (Fallahi et al., 2011) could be because fruit Ca concentrations were statistically similar in all treatments (Table 5). Fruit Ca has been shown to have a strong positive correlation with fruit firmness in apples (Fallahi et al., 1985c).

Leaf and fruit micronutrients. Trees receiving the FD treatment tended to have lower concentrations of leaf Fe, Zn, and Mn between 2004 and 2007, and averaging values over the years enhanced these differences (Tables 5, 6, and 7). There was no difference in the fruit Fe concentrations among irrigation treatments (Table 5).

Table 6. Effect of various irrigation regimes on leaf and fruit Zn and Cu concentrations in ‘Autumn Rose Fuji’ during 2004-2007.

Irrigation[z]	Leaf Zn (ppm)					Fruit Zn (ppm)					Leaf Cu (ppm)					Fruit Cu (ppm)
	2004	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07	Ave. 2004-07
FS	15 bc[y]	14 c	12 b	16 a	14 b	1.24 a	1.20 a	0.90 a	0.80 a	1.05 ab	9.4 a	8.3 a	7.5 a	7.8 a	8.3 a	2.76 a
PRS	18a	17 ab	15 a	16 a	16 a	1.40 a	1.17 a	0.65 b	0.98 a	1.07 ab	8.0 c	7.5 bc	6.8 b	7.2 a	7.4 b	2.38 b
FD	13 c	13 c	11 b	14 b	13 c	1.40 a	1.12 a	0.79 a	0.74 a	1.01 b	8.8 b	7.7 b	6.6 bc	7.3 a	7.6 b	2.35 b
DD	17 ab	18 a	16 a	16 a	16 a	1.40 a	1.27 a	0.85 a	0.95 a	1.30 a	8.2 c	7.6 bc	6.5 c	7.7 a	7.5 b	2.41 ab
PRD	17 ab	15 bc	12 b	13 b	14 b	1.26 a	1.12 a	0.61 b	0.70 a	0.96 b	7.0 d	7.3 c	6.6 bc	7.1 a	7.0 c	2.15 b

[z] Abbreviations: 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 five blocks, each with five trees.

Table 7. Effect of various irrigation regimes on leaf and fruit Mn and average water applications in ‘Autumn Rose Fuji’ during 2004-2007.

Irrigation[z]	Leaf Mn (ppm)					Fruit Mn (ppm)					Applied water (mm)	
	2004[y]	2005	2006	2007	Ave. 2004-07	2004	2005	2006	2007	Ave. 2004-07	Avg. 2004-05	Avg. 2006-07
FS	51 b	59 ab	55 a	54 a	55 ab	1.81 ab	2.37 ab	1.14 ab	1.43 ab	1.73 ab	722.3	994.0
PRS	59 a	62 a	54 a	49 a	56 a	1.63 b	2.27 ab	1.02 b	1.11 b	1.51 b	452.4	518.2
FD	51 b	53 b	47 bc	42 b	49 c	2.05 a	2.16 b	1.41 a	1.70 a	1.86 a	448.9	614.1
DD	58 a	61 a	42 c	43 b	51 bc	1.80 ab	2.46 ab	0.94 b	1.38 ab	1.74 ab	299.9	409.4
PRD	60 a	59 ab	50 ab	50 a	55 ab	1.63 b	2.27 ab	1.02 b	1.11 b	1.51 b	299.9	409.4

[z] Abbreviations: 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 five blocks, each with five trees.

Trees receiving FS irrigation had significantly higher leaf Cu than those under other irrigation treatments in three of four years in this study (Table 6) which agrees with the result for ‘Gala’ apple (Neilsen et al., 1995). Trees with PRD tended to have lower leaf Cu (Table 6). These observations suggest that a micro-sprinkler would be a preferred irrigation system when severe Cu deficiency exists. Since application of Cu-based fungicides in many orchards in the Pacific Northwest has reduced in the past 20-30 years, leaf Cu concentrations have declined, and elevation of leaf Cu may improve production and fruit quality.

Water application. The average precipitation (rainfall) during the 2004-2005 period, when trees were immature or at an early stage of maturity, was 60.6 mm, and the average for 2006-2007, when trees were mature, was 55.1 mm (data not shown). During the irrigation period in all years, July often had the lowest precipitation. Water application in all irrigation systems increased as trees matured (Table 7). Trees used the highest amount of water in July and August in all years. Trees with the FS treatment received a significantly greater volume of water than those with drip systems every year. On average, mature trees with a FS system received 994 mm (6461 L of water per tree), while those with a FD system received 614 mm (3996 L of water per tree) over the 2006 and 2007 seasons (Table 7). 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 7). Although the volume of water applied to the trees with DD or PRD was only 65% of that applied to the trees with an FD system, only minor water stress symptoms were observed in the trees with DD or PRD systems and 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 sprinkler or drip irrigations had smaller tree canopies and slightly earlier leaf senescence in late October, perhaps due to increased stress and ethylene production in the trees with lower irrigation.

Leib et al. (2006) compared three micro-sprinkler irrigation systems in mature 'Fuji' trees in Washington State. In that study, the soil water content under conventional irrigation (CI) was maintained close to field capacity, which was only 60-70% of estimated ETc for apples without a 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 evapotranspiration (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 in 2006 and 2007, the two-year average for ETr was 1106.6 mm and for ETc was 1050.3 mm (data not shown), and thus, these values were about 11% and 25% higher than the similar measurements in Washington, respectively. During 2006 and 2007, we applied an average of 994 mm of water to our FS trees (Table 7), which was about 287 mm (about 29%) higher than the levels applied to the CI treatment in the three-year report by Leib et al. (2006) in Washington State. This difference is perhaps largely due to the higher ETr and ETc values in Idaho than in 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, while CI trees in their experiment received water at about 70% of ETc. Rainfall in both experiments was somewhat comparable.

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, calculated based on full ETc rate and adjusted for ground cover, can result in major water saving and often improved yield and fruit quality. Application of water at full ET rates (FS and FD) resulted in higher leaf size and leaf K but reduced leaf Mg and Zn. Application of irrigation through a FS system increased leaf Cu and is potentially a preferred method of irrigation for those areas with Cu deficiency. Leaf Ca in trees with a FS system was higher than in those with a FD system but no significant differences were found among different irrigation systems in fruit Ca concentrations.

With an increasing demand for newer cultivars, higher orchard density, and different canopy architectures, the impact of various irrigation systems and rates of water application on fruit quality, yield, and mineral partitioning of apples need to be further studied, especially in the western and mid-western regions of the United States where water resource is scarce.

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