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Long-Term Influence of Irrigation Systems on Postharvest Fruit Quality Attributes in Mature 'Autumn Rose Fuji' Apple Trees

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ABSTRACT

In a long-term study between 2008 and 2011, effects of various evapotranspiration-based (ETc) irrigation systems on yield and fruit quality attributes of fully matured 'Autumn Rose Fuji' apple trees (*Malus* × *domestica* Borkh) after 5 months of regular atmosphere storage were examined. Trees with a full sprinkler (FS) system received about 39% more water than those with a full drip (FD) system over the period of 2008–2011. Fruits from trees with FS and FD were larger, while those with 50%FS were smaller than those from all other irrigation treatments. Averaging values over 4 years revealed that applications of any form of deficit irrigation, either by microjet irrigation or by drip, increased fruit-soluble solid concentration and firmness but decreased water core after storage. Trees receiving FS and FD systems (full irrigation systems) had lower fruit firmness reduction after storage than the treatments receiving deficit irrigation systems. Considering yield, and quality attributes in this study, a well-calculated ETc-based FD irrigation system is recommended over any other irrigation regime.

KEYWORDS
Deficit irrigation; drip irrigation; sprinkler

As the world population increases, efficient use of water in agriculture becomes more critical. Application of well-designed high-density orchards with efficient irrigation systems can result in lower water consumption (Fallahi et al., 2007) while producing higher quality fruits (Behboudian and Mills, 1997; Behboudian et al., 2005; Fallahi et al., 2007; Neilsen et al., 2010). 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 the North America (Fallahi et al., 2001, 2007; Neilsen et al., 2009).

Application of deficit irrigation resulted in reduction of yield and fruit size in 'Golden Delicious' apple in Israel (Naor et al., 2008). Drake et al. (1981) indicated that a reduction in water application may result in reduction in apple firmness, relating this observation to the advanced maturity in fruits

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with water stress. In contrast, other researchers have shown that apples from nonirrigated plots were firmer than those from irrigated plots (Assaf et al., 1975; Guelfat-Reich and Ben-Arie, 1979).

Irrigation with a drip system uses less water than sprinkler irrigation (Fallahi et al., 2007; Proebsting, 1994). However, irrigation through microjet sprinkler systems can improve the establishment and maintenance of orchard floor vegetation. Although there has been some progress in understanding microirrigation systems and N application (Fallahi et al., 2001; Neilsen et al., 2009), information on yield and fruit quality after storage in new apple cultivars under various regimes of drip or microjet 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 microjet sprinkler and three drip systems, using an ETc-based water scheduling, on water use, yield, and post-harvest fruit quality attributes in fully mature 'Autumn Rose Fuji' apple trees.

Materials and methods

Orchard establishment and general cultural practices

The experimental orchard was established at the Parma Research and Extension Center, University of Idaho in the spring and early-summer 2002. 'Autumn Rose Fuji' trees on RN.29 (Nic 29) rootstock (Columbia Basin Nursery, Quincy WA) were planted at 1.52 × 4.27 m spacing with an east–west row orientation. 'Snow Drift' crab apple on RN.29 rootstock (C & O Nursery, Wenatchee, WA, USA) 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. Tree leaders were maintained at approximately 3.55 m in height. The experimental site was located at 43.7853° N, 116.9422° W and had a semiarid climate with an annual precipitation of approximately 297 mm on a sandy loam soil of approximately pH 7.3.

In general, cultural practices other than irrigation were similar to those recommended for commercial orchards in the Pacific Northwest (Washington State University, 2017). 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, USA) and Ethephon (21.7% a.i.; Ethrel [(2-chloroethyl) phosphonic acid]; Bayer Crop Science) at a rate of 0.125% to 0.156% 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% 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, USA) was sprayed for sunburn protection at the rate of 56.8 kg ha^{-1} in early July, followed by three 1-week interval applications, each at 28.4 kg ha^{-1} every year.

Nitrogen as UAN 32 (urea and ammonium nitrate, 32% N) was applied at the total annual rate of 40 or 80 g N/tree via fertigation twice each year. The first half of N was applied at the rate of 20 g or 40 g/tree in late May and the second one was applied at the same rate 2 weeks after the first application each year. Potassium (when used) was applied as potassium oxide, 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. Calcium (Ca) and micro-nutrients, particularly, iron (Fe) and zinc (Zn), in chelated amino acid-based formulas (Ca–metalosate, Fe–metalosate, and Zn–metalosate, respectively; ALBION PLANT, Layton, UT, USA) were sprayed twice in spring and once in early summer each year.

Irrigation regimes and calculation

Five irrigation regimes were applied on each of the five experimental rows. These treatments were:

(1) Full sprinklers (FS). A 30-cm microjet sprinkler (Olson Ultra-jet, Santee, CA, USA), with water delivery capacity of 36.71 $L.hr^{-1}$, was connected to the lateral polyethylene line between every two trees. In this treatment, trees were irrigated once a week at the rate of cumulative daily full evapotranspiration (ETc) for the past week for apples starting in 2002. Method for ETc calculation is in the "Calculation for water application" section below.
(2) 50% full sprinkler (50%FS). This system was identical to the FS system (as described earlier), except that trees received only 50% of the volume that was applied to the trees with FS once a week, starting in 2002.
(3) Full drip (FD). One 16-mm drip line (Rain Bird Corporation, Azusa, CA, USA) was installed in a 10-cm trench (subsurface), 30 cm away from and parallel to the tree row on each of the north and south sides of the tree row. Trees in this system were irrigated twice a week, each time at the rate of cumulative full daily ETc of previous 3 to 4 days, but adjusted for the ground shading (GS) area. Therefore, in this treatment, liters of water applied per tree = (ETc in mm/percent drip efficiency factor) × 1.52 × 4.27 m spacing × %GS.
(4) 65% deficit drip (65%FD). This system was similar to FD system, except that the amount of water applied in this system was 65% of that applied to FD during 2008–2011.

(5) 50% deficit drip (50%FD). This system was similar to FD system, except that the amount of water applied in this system was 50% of that applied to FD during 2008–2011.

Calculation for water application

Irrigation started in about mid-May and ended in mid-October every year. Details of calculation for the amount of irrigation in each system were described in an earlier report (Fallahi et al., 2017). In general, water requirements were calculated based on ETc where ETc = ETr × 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 2002, the crop water use coefficient was calculated as: Kc = Kc base + %M × (mature Kc – Kc base). Percent canopy maturity (%M) was a measurement of canopy size and was calculated as: %M = 3.05 + 2.558 × (%GS) – 0.016 × $(\%GS)^2$. 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–(0.61×2)]/4.27 = 0.71]. Kc values for mature trees were used during the course of this experiment (2008–2011). Since crested wheatgrass was planted as the orchard floor cover plant, value for mature Kc for each month was adopted from Proebsting (1994) 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.

Yield and quality attributes

Yield per tree was recorded at harvest time. Yield per hectare can be calculated as: yield per tree multiplied by 1537 (which is the number of trees per hectare at the density of this study). Twenty fruits were randomly sampled from each tree on October 17–20 during 2008–2011 and average fruit weight was calculated. Ten of these fruits were used for evaluation of fruit quality attributes at harvest and the other 10 were kept in a regular atmosphere storage at °C for 5 months. After storage, quality attributes including fruit actual firmness, firmness loss (firmness reduction between harvest and post storage), SSC, percentage of SSC increase after storage, water core, "skin waxiness," and bitter pit were measured every year from 2008 through 2011. Soluble solid concentration was measured by a temperature-compensated refractometer (Atago N1, Tokyo, Japan). Fruit firmness was measured with a Fruit Texture Analyzer (Guss, Strand, Western Cape, South Africa).

Experimental designs and statistics

The experimental design was a randomized complete block split plot with five irrigation treatments as the main effects, two levels of nitrogen (N) as subplot, and five blocks (replicates). Each irrigation block contained 10 trees, where five of the adjacent trees randomly received 40 g actual N/tree/season, while the other five trees received 80 g actual N/tree/season. Since N levels did not have any impacts on yield or quality attributes other than fruit color, only results for irrigation are presented in this report. In Tables 1 and 2, mean separation within columns by LSD at 5% level. Each value within each year represents the average of 5 blocks, each with 10 trees. The assumption of normal data distribution was checked by computing univariate analyses for all tree responses in this study. Analyses of variance were conducted using SAS (SAS Institute, Cary, NC, USA), with General Linear Model and means compared by least significant difference (LSD) at $P \leq 0.05$.

There was no interaction between year, water, and N treatments for the amount of applied water, tree growth, or yield in this study. Thus, in addition to the results for these parameters, in each year, results of overall years from 2008 through 2011 are reported in this article.

Results and discussion

Effects of irrigation treatments on water usage, yield, and postharvest fruit quality

On average, trees with a FS system received 39% more water than those with a FD system over the period of 2008–2011 (Table 1). Averaging values over the four seasons showed that mature trees with a FS system received 5927.6 L of water per tree, while those with a FD system received 3610.3 L of water per tree per season (Table 1). Each tree with 50%FS received more water than those of 65%FD and 50%FD systems (Table 1).

Trees with FS and FD systems had higher yield per tree than trees with other systems (Table 1). Since trees with a FD system received less water than those with a FS system and had higher yield per tree than those with 50%FS, 65%FD, and 50%FD (Table 1), we suggest that FD is a preferred method of irrigation over other systems for ‘Autumn Rose Fuji’ apples as far as yield and water consumption factors are considered. Trees with FS and FD irrigation always had larger trunk cross sectional area and more new shoots and foliage (data not shown) than those with other treatments in 2008–2011.

Fruits from trees with FS and FD were significantly larger than those from all other treatments (Table 1). Fruits from trees receiving 50%FS treatment were significantly smaller than those from all other treatments. This observation suggests that trees require irrigation at full ET_C rates in order to produce larger fruits,

Table 1. Effects of different irrigation regimes on volume of applied water, yield, fruit weight, and firmness of 'Autumn Rose Fuji' in 2008–2011.

Irrigation[a]	Water applied Per season avg. 2008–11 (L/tree)	Yield average 2008–2011 (kg/tree)	Fruit weight avg. 2008–2011 (g)	Firmness after storage (Newton) 2008	2009	2010	2011	Average 2008–2011	Firmness at harvest average 2008–11 (Newton)	Firmness loss average 2008–11 (Newton)
FS	5927.6	34.5 a	262.4 a	79.7 c	74.2 bc	73.9 c	75.2 b	75.7 c	78.6 d	2.68 b
50%FS	3133.1	23.5 b	184.4 c	85.4 a	83.2 a	84.0 b	81.1 a	83.4 a	87.3 a	4.00 ab
FD	3610.3	34.4 a	255.5 a	79.7 c	72.8 c	80.8 b	75.7 b	77.3 c	80.8 c	3.38 b
65%FD	2433.0	27.5 b	208.7 b	83.9 ab	72.9 c	88.5 a	75.2 b	79.7 b	83.9 b	3.93 ab
50%FD	1922.2	24.7 b	207.3 b	81.5 bc	76.1 b	81.2 b	81.0 a	79.8 b	85.2 b	5.37 a

[a]Abbreviations: Irrigation applied to the trees: FS = full sprinklers (microjet, applied at 100% ETc); 50%FS = 50% of FS; FD = Full drip, applied at 100% ETc, adjusted for ground shading; 65%FD = 65% of FD; 50%FD = 50% of FD.

[b]Mean separation within columns by LSD at 5% level. Each value within each year represents the average of five blocks, each with 10 trees.

and reduction of water application to 50%FS, 65%FD, and 50%FD will result in fruit size reduction.

Although the volume of water applied to the trees with 50%FS was more than that applied to the trees with 65%FD and 50%FD treatments (Table 1), fruit weight in trees with 65%FD and 50%FD was significantly heavier than those with 50%FS (Table 1). This result indicates that if water usage is mandated and when fruit weight is not of a major component of apple production, the use of 65%FD or 50%FD is more beneficial than the use of 50%FS for maintaining trees.

Fruit firmness of all treatments decreased in the storage. Averaging values over 4 years revealed that trees receiving FS and FD treatment had lower firmness at harvest and after storage than those receiving deficit irrigation (50%FS, 65%FD, and 50%FD) (Table 1). Trees receiving FS and FD systems (full irrigation systems) had significantly lower fruit firmness reduction than the treatments receiving deficit irrigation systems (Table 1). Higher water content of fruit with FS and FD system could have maintained a higher cell turgidity, leading to a lower firmness reduction in the storage. Our results are in general agreement with other researchers who showed that apples from nonirrigated plots were firmer than those from irrigated plots (Assaf et al., 1975; Guelfat-Reich and Ben-Arie, 1979). Assaf et al. (1975) indicated that fruits from trees subjected to water deficiency were smaller and thus firmer than those from conventionally irrigated trees. In contrast, Drake et al. (1981) reported that low water application may reduce apple firmness, because of the advanced maturity in fruits with water stress in 'Golden Delicious'. Leib et al. (2006) observed that firmness of 'Fuji' apple was not affected by deficit irrigation treatments in five out of six different measurements during 2001–2003. Also, Talluto et al. (2008) showed that fruit firmness was not affected by deficit irrigation treatment in 'Pink Lady' apple. These observations suggest that the impact of deficit irrigation 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-deficit irrigation interactions.

Averaging over 4 years showed that fruits from trees with 50%FS had significantly higher, while those from trees with FS and FD systems had lower SSC at harvest and after storage (Table 2). Fruit SSC in all treatments increased after storage, and the rates of increase in FS and FD treatments were greater than those in other treatments (Table 2). Starch degradation patterns in fruit from trees receiving FS and FD were lower at harvest (data not shown), suggesting a lower hydrolysis of starch in these fruits. Therefore, fruits from FS and FD had higher starch reserve at harvest, resulting in a higher conversion of starch to SSC after storage. Our results are in agreement with some of the previous researchers who reported 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 (Mpelasoka et al., 2000, 2001). Leib et al. (2006) showed that SSC in fruit from trees receiving deficit irrigation was

Table 2. Effects of different irrigation regimes on postharvest soluble solid concentration, water core, waxy skin, and bitter pit of 'Autumn Rose Fuji' in 2008–2011.

	Soluble solid concentration (SSC) after storage (% Brix)							Water core (%)						
Irrigation[a]	2008	2009	2010	2011	Average 2008–2011	SSC at harvest average 2008–2011 (%Brix)	SSC increase in storage average 2008–2011 (%)	2008	2009	2010	2011	Average 2008–2011	Waxy skin average 2008–2011 (%)	Bitter pit average 2008–2011 (%)
FS	15.33 c	15.48 bc	15.75 c	14.37 b	15.24 d	14.83 d	2.69	4.8 b	1.20 a	6.3 b	0.53 a	3.0 b	1.19 c	2.4 a
50%FS	16.53 a	16.61 a	17.15 a	15.00 a	16.35 a	16.12 a	1.41	4.2 b	0.76 a	2.3 b	0.25 a	1.4 b	43.6 a	0.93 a
FD	15.60 bc	15.24 c	16.26 bc	14.32 b	15.39 cd	15.04 d	2.27	11.6 a	0.10 a	15.2 a	0.10 a	6.9 a	0.1 c	3.04 a
65%FD	15.38 c	15.45 bc	17.22 a	14.36 b	15.60 c	15.43 c	1.09	4.2 b	0.10 a	5.3 b	0.10 a	1.9 b	20.8 b	1.75 a
50%FD	16.03 b	15.86 b	16.45 b	15.56 a	15.93 b	15.70 b	1.44	1.5 b	0.10 a	2.5 b	0.10 a	0.87 b	22.5 b	2.21 a

[a]Abbreviations: Irrigation applied to the trees: FS = full sprinklers (microjet, applied at 100% ETc); 50%FS = 50% of FS; FD = Full drip, applied at 100% ETc, adjusted for ground shading; 65%FD = 65% of FD; 50%FD = 50% of FD.

[b]Mean separation within columns by LSD at 5% level. Each value within each year represents the average of five blocks, each with 10 trees.

higher than in fruit from trees receiving conventional irrigation. In contrast, Talluto et al. (2008) reported that 'Pink Lady' fruits from deficit and full irrigation 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 the contradictory results from different researchers.

Trees receiving a FD treatment had higher percentages of poststorage water core than those receiving other irrigation treatments in 2 of 4 years of evaluation (Table 2). Marlow and Loescher (1984) 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' apples. The exact mechanism for the presence of higher water core incidence in the FD treatments deserves further study.

Application of irrigation at a full ETc rate (FS and FD) significantly reduced "waxy skin" disorder (Table 2). Thus, this disorder seems to appear when trees do not receive sufficient water. Irrigation systems did not have any impact on bitter pit incidence after storage (Table 2).

Conclusion

A significantly greater volume of water is required for trees under full microjet 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 improve yield and fruit quality attributes. Application of 50%FS reduces yield and fruit weight, while it may improve fruit SSC and firmness. Fruit firmness of all treatments decreased in the storage. Averaging values over 4 years revealed that trees receiving FS and FD treatment had lower firmness at harvest and after storage than those receiving deficit irrigation (50%FS, 65%FD, 50%FD). Trees receiving FS and FD systems (full irrigation systems) had significantly lower fruit firmness reduction than the treatments receiving deficit irrigation systems. Fruit from trees with 50%FS had significantly higher, while those from trees with FS and FD systems had lower SSC at harvest and after storage. Fruit SSC in all treatments increased after storage, and the rates of increase in FS and FD treatments were greater than those in other treatments. Considering growth, yield, and fruit quality attributes in this study, a well-calculated ETc-based FD irrigation system is recommended over any other irrigation regime for modern high-density apple orchards. 'Autumn Rose Fuji' apple trees can be maintained with drip irrigation at 65% of drip ETc rate (i.e., 65%FD) if certain fruit quality attributes, such as fruit weight, are not of major concern for production.

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Disclosure statement

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