Regulated Deficit Irrigation of ‘Montmorency’ Tart Cherry

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Abstract. Mature tart cherry (*Prunus cerasus* L. ‘Montmorency’) trees in a commercial orchard were subjected to irrigation deficits from pit hardening to harvest during the 2007 and 2008 seasons. Irrigation treatments ranged from 30% to 100% of a commercially managed application rate during the deficit period. Midday stem water potential measurements were significantly different among treatments before harvest. However, fresh weight yield at harvest did not differ significantly among irrigation treatments in either year ($P = 0.64$). In 2008, the amount of undersized fruit eliminated during packout was significantly higher in the treatments replacing 30% and 47% of the commercial irrigation level ($P < 0.001$), but only amounted to 2.0% and 1.4% of total yields, respectively. This small increase in undersized fruit did not significantly affect packout. Soluble solids concentration and chroma of intact fruit increased with the severity of the irrigation deficit and were inversely correlated with fruit water content.

In the arid western United States, the availability of water for agricultural purposes is becoming limited, particularly in years when reduced winter precipitation decreases mountain snowpack. When water resources are limiting, growers need to manage their water more effectively in an attempt to maximize water productivity. Water productivity (Feres and Soriano, 2007) is the crop yield or net income per unit of water used in crop evapotranspiration (ET_c). Under drought conditions, irrigation scheduling needs to be evaluated to maximize water productivity. In perennial crops such as fruit orchards in which management in 1 year affects the crop in the next season, both water productivity and the long-term health of the orchard need to be considered.

Regulated deficit irrigation (RDI) is the strategy of supplying reduced irrigation rates during specific phenological stages and optimal irrigation for the remainder of the irrigation season to manage crop growth and water efficiency. The objectives of RDI are to save water, control excessive vegetative growth

(Chalmers et al., 1981), and, where possible, improve or maintain yield and fruit quality. RDI studies have been carried out in Australia, California, Israel, and Spain on fruit and nut crops such as grape, apple, pear, peach, plum, prune, apricot, almond, nectarine, and olive.

Stone fruit crops have three fruit growth stages. Stage I growth is characterized by rapid cell division. Stage II is also known as the lag period because there is little visible fruit expansion and is characterized by pit hardening. During Stage III, fruit growth results from expansion of the cells and the intercellular spaces, and the fruit ripen before harvest. Stage II is the period most often targeted by RDI but is of variable duration and may be indistinguishable for early-maturing fruit such as early peach cultivars (Grossman and DeJong, 1995). In apricot, the majority of shoot growth is completed before pit hardening, so RDI during Stage II may not provide vegetative control in mature trees (Torrecillas et al., 2000).

Research on peach and apricot has indicated that yield, fruit size, and fruit quality can be maintained under conditions of mild to moderate drought stress applied during Stage II and occasionally during Stages I and II together (Girona et al., 2005; Pérez-Pastor et al., 2009; Torrecillas et al., 2000). More severe deficits such as complete irrigation cutoffs or deficits applied up to harvest have resulted in fruit size decreases (Intrigliolo and Castel, 2005; Torrecillas et al., 2000). For crops that are processed and dried such as prune and tart cherry, the dry weight yield is more economically important than the fresh weight yield. For prune, gradually increasing drought stress up to harvest resulted in decreased fresh weight yields that were offset by increases in percent dry matter (no dry matter yield loss) with irrigation savings of 40% (Shackel et al., 2000).

A few reports have been published on RDI research of sweet cherry (Antunez-Barria, 2006; Dehghanian et al., 2007), but there is limited RDI research for tart cherry. In the

fruit-growing areas of the Intermountain West region of the United States, much of the annual precipitation comes in the form of winter snow and early spring rains. Except in sandy soils, irrigation is typically not needed in tart cherry until mid to late Stage II, and imposing irrigation deficits is not possible until Stage III. However, Stage III irrigation deficits could provide a means of water conservation while maintaining or improving quality of a processed fruit. The objective of this work was to study the effects of different levels of RDI applied during Stage III fruit growth (pit hardening to harvest) on fruit size, fruit quality, and yield of ‘Montmorency’ tart cherry.

Materials and Methods

The trial was conducted in 2007 and 2008 in a commercial tart cherry orchard (*Prunus cerasus* L. cv. Montmorency on Mahaleb rootstock) planted in 1994 in Santaquin, UT (39.99° N lat., 111.80° W long.; elev. 1480 m) on a Pleasant Vale loam soil with an available water-holding capacity of 76 cm·m⁻¹. The climate is semiarid with a 30-year mean (1979 to 2008) annual precipitation of 486 mm and mean precipitation during the growing season (1 Mar. to 31 Aug.) of 222 mm. Daily alfalfa-based reference evapotranspiration (ET_r) was calculated using the Kimberly-Penman equation (Dockter and Palmer, 2008; Jensen et al., 1990) with weather data taken from an automated station located within the orchard. Where problems existed with this weather station, data were taken from automated stations 3 and 4 km from the research orchard (Moller and Gillies, 2008). Orchard management, including fertility and pest management practices, were according to common commercial practices.

Orchard rows were oriented north to south with tree spacing of 4.3 × 5.5 m. A grass cover crop was planted between the rows and a 1.8-m weed free strip was maintained under the trees with the use of herbicides. Irrigation was applied with microsprinklers (Ultra-Jet 6900 OA; Olson Irrigation Systems, Santee, CA), one per tree, placed in the tree row midway between trees. Each microsprinkler was rated to deliver 106 L·h⁻¹ (at 225 kPa) and had a circular wetting pattern with a diameter of 7 m. Field-measured flow rate was 98 L·h⁻¹ at 225 kPa. Deficit treatments were established by exchanging the existing nozzles for nozzles with reduced flow rates. The field measured nozzle flow rates for the 100%, 77%, 60%, 47%, and 30% treatments were 98, 75, 59, 46, and 28 L·h⁻¹ at 225 kPa, respectively. To manage the frequency and length of irrigation applications, the grower/cooperator used soil volumetric water measurements (Diviner 2000; Sentek Sensor Technologies, Stepney, South Australia) and estimates of ET_c , based on calculated ET_r values from the weather station and crop coefficients published for sweet cherry (AgriMet, <http://www.usbr.gov/pn/agrimet/>). Application intervals and lengths varied over the season depending on crop water use and ranged from 4- to 10-d intervals and 10- to 12-h irrigation periods.

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The five irrigation treatments were applied to six replicate plots in a randomized block design with blocking by location in the orchard. Each experimental plot consisted of 36 trees spanning three rows with 12 trees per row. Data were collected from the 10 central trees of the middle row. Irrigation treatments were imposed beginning at the pit hardening stage of fruit development and continuing until harvest. Irrigation was discontinued in the orchard from 8 to 14 d before harvest to decrease soil compaction by the harvest equipment. Microsprinkler nozzles for the RDI treatments were replaced with the control nozzles immediately after harvest for the remainder of the irrigation season. Deficit irrigation treatments were repeated on the same plots in 2008.

Tree water status was determined with midday stem water potential (Ψ_{stem}) measurements (McCutchan and Shackel, 1992) 9 and 2 d before harvest in 2007 and 2008, respectively. Briefly, one leaf from each of three trees per plot was enclosed in a reflective bag for a minimum of 1 h. Measurements were taken within 1.5 h of solar noon using a pressure chamber (Model 610; PMS Instrument Company, Albany, OR).

Fruit quality was determined on fruit samples collected before harvest, from mechanically harvested fruit, or on commercially pitted and washed fruit. Preharvest samples were hand-picked 3 to 4 d before mechanical harvest. In total, 90 fruit were collected per plot. Fruit from the periphery of the canopy were randomly sampled at midtree height on the east and west sides of the row. Fruit samples were placed in plastic bags on ice, transported to the laboratory, and refrigerated for 1 to 2 d while being evaluated. Surface color was measured on one cheek of each fruit using a portable spectrophotometer (CM-2600d; Konica Minolta Sensing, Osaka, Japan). A 45-fruit subsample was pressed through a metal screen (0.17-cm pores) and the flesh mass (pitted fruit and juice) measured. Flesh samples were stored at -80°C until soluble solids concentration (SSC) and dry matter content were measured. Later, frozen flesh samples were thawed in a 30°C water bath and filtered (Whatman #1). A benchtop refractometer (Abbe-3L; Bausch and Lomb, Rochester, NY) was used to measure SSC. Samples were then freeze-dried to determine dry matter (FreeZone 12; Labconco, Kansas City, MO). Dry matter content was expressed as a percent of fresh weight.

Plots were mechanically harvested using a commercial trunk shaker system (Kilby Manufacturing, Gridley, CA) with harvested fruit collected in water-filled tanks. Yield was determined by measuring the depth of fruit in the tanks and converted to mass according to a standard commercial conversion ($7.94\text{ kg}\cdot\text{cm}^{-1}$; Chad Rowley, personal communication). Harvested yield was determined based on the accumulated fruit depths for one plot (10 trees). Fruit from six to 10 trees was sufficient to fill one tank, and a full tank ($\approx 480\text{-kg}$ fruit sample) from each plot was tracked through the packing plant to determine

packout. The tanks of fruit were cooled with flowing water (4°C) for a minimum of 4 h before pitting according to standard commercial practices. Subsamples of 100 fruit from each tank were collected and evaluated for undersized fruit using a sizing ring (less than 9.5 mm) and for the number of stems remaining attached to the harvested fruit. Ideally, mechanical harvest removes the fruit from the pedicel. Where excessive numbers of pedicels remain attached to the fruit, the higher stem count adversely affects packout. The 480-kg tank samples were then individually passed over a packing line with a stem remover, an eliminator chain that removed undersized fruit (less than 9.5 mm diameter) and mechanical pitters, and then packed in 11.3-kg buckets for freezing. The number of 11.3-kg buckets collected from each tank of fruit was recorded to determine packout. One bucket from each plot was commercially frozen and stored for a minimum of 4 months.

The commercially frozen samples were thawed for 2 d and then juice was drained from the fruit for 5 min. Subsamples of the juice were collected and stored at -80°C for subsequent color analysis. Juice samples were thawed in a 30°C water bath and filtered (Whatman #1). Aliquots of juice were further filtered through a $0.45\text{-}\mu\text{m}$ syringe filter and then diluted 1:4 by volume with distilled water ($800\text{ }\mu\text{L}$ distilled water to $200\text{ }\mu\text{L}$ juice) before measuring absorbance at 512 nm (Özkan et al., 2002) with a transmission spectrophotometer (SpectraMax M2; Molecular Devices, Sunnyvale, CA).

Treatment means were compared using PROC MIXED, analysis of variance (ANOVA) (Version 9.1; SAS Institute, Inc., Cary, NC). A treatment effect significant at $P \leq 0.05$ was further analyzed with the Tukey mean separation test. Treatment $\times$ year interactions were tested using repeated-measures ANOVA.

Results and Discussion

Weather conditions in Spring 2008 were cooler than in 2007, resulting in delayed bloom (8 May 2008 compared with 1 Apr. 2007). From March to May, the average maximum air temperature was 15.1°C in 2008 and 18.7°C in 2007 compared with the 30-year mean of 16.6°C (1979 to 2008). During the fruit development period (June to July), the average maximum temperature in 2008 was similar to the 30-year mean (30.1 and 30.3°C , respectively), whereas 2007 had higher temperatures (33.7°C). Precipitation from 1 May to

31 Aug. was greater in 2008 than either 2007 or the 30-year mean (Papenfuss, 2010).

The level of pit hardening was determined qualitatively by slicing random samples of 10 fruits to determine resistance. When endocarp hardening became noticeable, treatments were imposed beginning at the next irrigation cycle. Treatments were initiated on 24 May 2007 and 23 June 2008 corresponding to 53 and 46 d after full bloom, respectively, and replaced from 30% to 100% of commercially managed irrigation. The 100% treatment replaced $100\% \pm 5\%$ of calculated ET_c . Less water was applied in the 2008 irrigation season than in 2007 (Table 1). However, this was offset by greater precipitation in Spring 2008. Annual water savings for the deficit treatments ranged from 15% to 50%. The amount of irrigation applied was closely correlated with preharvest Ψ_{stem} in both seasons (Fig. 1).

Trees in RDI treatments had significantly lower Ψ_{stem} than the control. Before harvest in 2007, the most severe deficit treatment had a Ψ_{stem} of -1.17 MPa compared with -0.78 MPa for the control. Before harvest in 2008, Ψ_{stem} ranged from -0.86 MPa for the control to -1.25 MPa for the most severe deficit (Fig. 1). The tree response was very similar between years despite the seasonal differences in temperature and rainfall. These results indicate that altering irrigation flow rate with micro-spray nozzles was an effective method of imposing a range of irrigation deficits within an existing irrigation system. These Ψ_{stem} values were similar to those previously reported for RDI trials in peach (-1.2 MPa ; Girona et al., 2005), sweet cherry (-1.7 MPa and -1.5 MPa ; Antunez-Barria, 2006), plum (-1.2 MPa ; Intrigliolo and Castel, 2005), and prune (1.5 MPa ; Shackel et al., 2000). Antunez-Barria (2006) reported that the Ψ_{stem} threshold for reducing the net photosynthetic rate for sweet cherry was -1.5 MPa . Assuming a similar threshold for tart cherry, the deficits in the present study would have had little or no effect on photosynthetic rate.

For both years, crop loads were considered moderate for this orchard and region. There were no treatment effects on mean fresh weight yield for either year (Table 2). The percentage of undersized fruit was slightly greater in the 30% treatment (Table 3) but did not significantly affect packout (Table 2). Unlike fruits that are sold for fresh market, size in tart cherries is less critical in determining crop value. The primary concern is that fruit size is sufficiently large and consistent to allow for consistent mechanical pitting. Therefore,

Table 1. Seasonal irrigation and water savings for deficit irrigation treatments applied to 'Montmorency' tart cherry trees during Stage III fruit growth (pit hardening to harvest).^z

Treatment level (%)	Irrigation applied (mm)		Water savings (%)	
	2007	2008	2007	2008
100%	526	451	0	0
77%	440	382	16	15
60%	377	332	28	26
47%	328	293	38	35
30%	263	240	50	47

^zTreatment levels are percent of commercially managed irrigation during the deficit period.

Fig. 1. The effect of Stage III deficit irrigation on preharvest midday stem water potential (Ψ_{stem}) of 'Montmorency' tart cherry (9 and 2 d before harvest in 2007 and 2008, respectively). Data are the mean of six replicate plots with three trees sampled per plot. Treatment levels are the percent of commercially managed irrigation during the deficit period. The vertical bars indicate the SE of the mean.

Table 2. The effect of Stage III deficit irrigation on fresh weight harvest yield and packout of tart cherry.^z

Treatment level (%)	Yield (t/ha)			Packout (%)		
	2007	2008	Mean	2007	2008	Mean
100%	25.6	28.0	26.9	74.7	75.5	75.1
77%	26.6	25.8	26.2	73.0	75.4	74.2
60%	23.9	22.7	23.3	77.8	74.8	76.3
47%	26.6	24.7	25.7	74.4	75.4	74.9
30%	25.9	24.5	25.2	73.1	74.7	73.9
P	0.26	0.24	0.54 ^y	0.06	0.95	0.67

^zData for harvest yield are means of six replicate plots with 10 record trees per plot. Packout was the mass of packed fruit (pitted with undersized and damaged fruit removed) relative to ≈ 480 -kg samples of machine-harvested fruit. Treatment levels are percent of commercially managed irrigation during the deficit period.

^yThere was no significant year or treatment $\times$ year interaction for either yield or packout.

Table 3. The effect of Stage III deficit irrigation on the quantity of undersized (% less than 9.5 mm diameter) tart cherry fruit at packout.^z

Treatment level (%)	100-fruit subsample		480-kg sample
	2007	2008	2008
100%	0.2	0.3	0.9 b ^y
77%	0.5	1.0	0.9 b
60%	0.5	0.3	1.0 b
47%	0.3	0.5	1.4 a
30%	1.7	1.8	2.0 a
P	0.19	0.06	<0.001

^zUndersized fruit were determined on entire harvest tank samples (≈ 480 kg) and on a 100-fruit subsample for each plot. Treatment levels are percent of commercially managed irrigation during the deficit period.

^yMean separation by Tukey-Kramer at $P < 0.05$.

Table 4. Effect of Stage III deficit irrigation on dry matter content (%), soluble solids concentration (SSC), surface color intensity (chroma), and juice color (absorbance at 512 nm) of 'Montmorency' tart cherry fruit.^z

Treatment level (%)	Dry matter content (%)		SSC (%)		Surface chroma		Juice color (abs. at 512 nm)	
	2007	2008	2007	2008	2007	2008	2007	2008
100%	14.4 B ^y	13.8 B ^y	14.1 B ^y	13.3 B ^y	21.9 c ^y	24.6	32.9 b ^y	43.8
77%	14.3 b	13.8 b	14.0 b	13.4 b	22.3 bc	24.4	34.0 ab	45.1
60%	14.6 ab	14.1 b	14.3 b	13.5 b	22.7 abc	24.8	32.5 b	44.2
47%	14.7 ab	14.1 ab	14.4 ab	13.7 ab	23.1 ab	24.3	34.1 ab	45.7
30%	15.3 a	14.8 a	14.9 a	14.3 a	23.3 a	25.1	38.0 a	50.1
P	0.007	0.002	<0.001	<0.001	<0.001	0.14	0.008	0.06

^zDry matter content, SSC, and surface color were determined on hand-harvested samples and are means of six replicate plots with 45 fruits sampled per plot. Juice color was determined on commercially harvested and packed fruit. Treatment levels are percent of commercially managed irrigation during the deficit period. Values are the means of six replicate plots.

^yMean separation by Tukey-Kramer at $P < 0.05$.

undersized fruit are eliminated before pitting to allow consistent pit removal. Thus, the RDI regime used here effectively reduced irrigation water use without adversely affecting yield or packout for the moderate crop loads of 2007 and 2008. Naor (2006) reported for apple that as the number of fruit (crop load) increases, the effect of water stress on fruit size intensifies. The correlation of Ψ_{stem} with fruit size was reported for nectarine under deficit irrigation during Stage III with r^2 values ranging from 0.61 to 0.78 (Naor et al., 2001). However, the present study showed no correlation between tart cherry tree Ψ_{stem} and undersized fruit ($r^2 = 0.19$). This was probably the result of the relatively moderate levels of both water stress and crop load, in which Ψ_{stem} in the most severe RDI treatment was ≈ -1.3 MPa just before harvest compared with -2.5 MPa in the nectarine trial (Naor et al., 2001).

There were some treatment effects on fruit quality, including dry matter content (%), SSC, and fruit surface chroma. Fruit dry matter content (%) increased with severity of RDI in both seasons (Table 4). Fruit SSC and surface chroma (color intensity) also increased with the severity of RDI (Table 4) and were correlated with fruit dry matter content (data not shown). Dry weight per fruit did not differ among treatments, indicating that treatment differences in fruit dry matter content (%) were the result of fruit water content (Naor, 2006) and not osmotic adjustment (Antunez-Barria, 2006; Hsiao et al., 1976). RDI did not affect other fruit quality factors, including stem number, firmness, damage, blemishes, pit removal, titratable acidity, surface hue, or lightness (see Papenfuss, 2010). The effect of RDI on tart cherry dry matter content, SSC, and chroma would likely be beneficial for dried cherry processing.

Return bloom in both 2008 and 2009 was strong and showed no detectable differences among irrigation treatments (Papenfuss, 2010; Papenfuss et al., in press). Fruit set in 2008 was reduced somewhat by a late spring frost but was unusually heavy in 2009 with no detectable treatment differences in either year. The indications of this trial are that tart cherry yield and fruit quality may be safely maintained with annual irrigation savings of $\approx 30\%$ in moderate crop years. More severe deficits increase the risk of undersized fruit, which would likely be accentuated in heavy crop years. More research is needed to evaluate the long-term effects of Stage III irrigation deficits on the health of 'Montmorency' tart cherry trees.

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