5-2010

Regulated Deficit Irrigation of 'Montmorency' Tart Cherry

Kylara A. Papenfuss
Utah State University

REGULATED DEFICIT IRRIGATION OF ‘MONTMORENCY’ TART CHERRY

by

Kylara A. Papenfuss

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Plant Science

Approved:

Brent Black, Ph.D. Major Professor	Robert Hill, Ph.D. Committee Member
Richard Mueller, Ph.D. Committee Member	Byron R. Burnham Dean of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2010

ABSTRACT

Regulated Deficit Irrigation of 'Montmorency' Tart Cherry

by

Kylara A. Papenfuss, Master of Science

Utah State University, 2010

Major Professor: Dr. Brent Black
Department: Plants, Soils, and Climate

Regulated deficit irrigation (RDI) is the strategy of reducing irrigation rates during a specific period of growth and development, with the objective of conserving water and managing plant growth while maintaining or improving yield and fruit quality. Mature tart cherry (*Prunus cerasus* L. 'Montmorency') trees in a commercial orchard were subjected to a range of irrigation deficits from pit hardening to harvest during the 2007 and 2008 seasons. Irrigation treatments replaced from 62% to 96% of crop evapotranspiration, ET_c, during that 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-value = 0.64). In 2008 the amount of undersized fruit eliminated during packout was significantly higher in the treatments replacing 61% and 68% of ET_c than in the control (P-value < 0.0001), but only amounted to 2.0 % and 1.4 % of total yields, respectively. This small increase in undersized fruit did not significantly affect packout. Fruit quality measurements, such as soluble solids concentration and chroma of whole intact fruit, increased with the severity of the irrigation deficit. Visible surface bark damage from mechanical harvesting appeared less severe as deficit levels increased. Return bloom was not significantly affected by irrigation treatments.

(61 pages)

ACKNOWLEDGMENTS

I would like to thank my friends and family for the support that they have shown during this chapter in my life. This has been a period of growth and learning, both stressful and enjoyable, as I have shared my joys and sorrows with my friends. My committee has been invaluable at this time, giving quiet encouragement, as well as sage advice from their field of expertise and their experience. Also, I would like to give special thanks to my dad and James (our technician) for their hours of assistance in the field work relating to this project, as well as letting me talk my way through problems and uncertainties. My mother deserves more praise than I can give her; her gentle encouragement and loyalty smoothed many rough spots on the way. To all of the people left unnamed I am especially grateful, those who helped me out of the goodness of their hearts, owing me no loyalty. Most importantly I would like to show gratitude to my Creator for his manifold blessings and for the peace and love that filled my soul when the pain of my sister's passing and the trials of life became overwhelming. I hope in some way I can serve Him, as I have been served.

Kylara A. Papenfuss

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Utah is ranked as the second largest producer of tart cherries in the nation, producing 28 million pounds (12,700 Mg), or about eight percent of the U.S. total (U.S. Department of Agriculture, 2006). Cherries are a popular fruit in the U.S. and are versatile, flavorful, and highly nutritious. Annual consumption of processed cherries in the U.S. (90% tart cherries) is one pound (0.454 kg) per person (Pollack and Perez, 2002). In Utah, tart cherry orchards make up 47% of the tree fruit acreage, with 90% of the acreage found in Utah County (U.S. Department of Agriculture, 2006). Thus, improving the yield and efficiency of tart cherry production would be economically important on both the state and national level.

Water resources in Utah are often limiting for agricultural purposes, particularly in years with a reduced snowpack. Guidelines for when to apply limited irrigation supplies would assist efforts to optimize yield and fruit quality in the present, and to maintain the long-term health and longevity of the orchard. For instance, severe drought stress during blossom development of one season may detrimentally affect bloom in the following season. However, there are periods during the growing season when vegetative or reproductive growth is less demanding of resources. In a mature orchard, withholding water during active vegetative growth could reduce pruning requirements. In a young orchard however, vegetative growth is necessary to establish fruiting wood and branches for photosynthesis.

The strategy of regulated deficit irrigation (RDI) was developed in Australia in a young high density peach orchard. The deficit was applied during the lag phase of fruit growth, known as stage II or pit hardening. In this case, yields were improved and vegetative growth was limited, resulting in improved light penetration through the canopy (Chalmers et al., 1981). This study led to extensive research in Australia, California, Israel, and Spain on fruit and nut crops such as grape, apple, pear, peach, prune, almond, nectarine, olive, plum, and apricot. A few reports have been published on RDI research of sweet cherry (Antunez-Barria, 2006; Dehghanisanij et al., 2007), but there is limited RDI research for tart cherry.

Stone fruit crops have three fruit growth stages: stage I is where reproductive cell division occurs, stage II covers the process of pit hardening, and stage III is fruit expansion prior to harvest. Stage II is known as the lag period as there is no visible fruit expansion, and is the period where RDI is most often applied. However, stage II is of variable duration, and is often indistinguishable for early-maturing fruit. For example, an early variety of peach had no apparent period of reduced fruit growth between bloom and harvest (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 until 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 tends to be more economically important than the fresh weight yield. This distinction was reported with prune, where progressively decreasing fresh weight yields were offset by increases in percent dry matter (no dry matter yield loss), with irrigation savings of 40% (Shackel et al., 2000).

Early RDI techniques only used postharvest deficits because of the sensitivity of fruit expansion to water stress. This management strategy is effective for some fruit crops, but not for those with more sensitive postharvest bud development. Postharvest water stress may cause damage during fruit bud differentiation, resulting in lower fruit set the following year (Girona et al., 2005; Goldhamer and Viveros, 2000; Torrecillas et al., 2000). However, when drought is gradually imposed after harvest, the period of bud differentiation is not affected by water stress, and thus the flowering and fruit set of the following season is not affected (Intrigliolo and Castel, 2005). Moderate preharvest drought stress may increase bloom density (Goldhamer and Viveros, 2000; Romero et al., 2004; Shackel et al., 2000). However, yield losses may still be incurred if vegetative growth is reduced, resulting in fewer fruit per tree. Drought stress did not affect the number of double fruit (two fruits fused together) in sweet cherry or plum, possibly due to fruit being carried on spurs instead of on one-year-old shoots (Beppu and Kataoka, 1999; Intrigliolo and Castel, 2005).

It is generally maintained that RDI may be used successfully to manage plant growth. The water stress sensitivity of different organs and the reproductive and vegetative growths stages of a crop must be considered in order to develop a successful RDI regime. In peach, water stress sensitivity is highest for limb diameter increase, followed by shoot elongation growth, fruit growth, and expansion in leaf area (Li et al., 1989). Variable results are often due to physiological stresses other than water that are affecting tree growth, such as cultural practices, tree age and health, crop load, and soil properties (Grimplet et al., 2007).

RDI may reduce vegetative growth in both branch length and trunk diameter (Girona et al., 2005; Intrigliolo and Castel, 2005; Romero et al., 2004), or may not change growth compared to the control (Pérez-Pastor et al., 2009; Torrecillas et al., 2000). A reduction in vegetative growth may also affect the cambial growth patterns, and may play a role in reducing bark damage due to structural changes of the cambium when it enters dormancy, such as a cell wall thickening (Lachaud, 1989). Irrigation cutoffs applied to 14-year-old almond trees before harvest resulted in a non-significant trend of less visible bark injury from mechanical harvest with increased length of irrigation cutoffs (Goldhamer and Viveros, 2000). Another measurement related to bark injury is bark shear strength. Bark shear strength of almonds under different deficit irrigation regimes showed no correlation with either trunk radial growth rate or water stress (Gurusinghe and Shackel, 1995).

The objective of this work was to study the effects of different levels of RDI applied from pit hardening to harvest on flowering, fruit size, fruit quality, yield, and the susceptibility of the trunk to bark damage during mechanical harvest. The work was carried out in a commercial orchard in Utah County to demonstrate the potential of RDI in managing yield, fruit quality, and tree health.

Literature Cited

Antunez-Barria, A.J. 2006. The impact of deficit irrigation strategies on sweet cherry (*Prunus avium* L) physiology and spectral reflectance. Washington State Univ., PhD Diss., (UMI Microform 3252310).

Beppu K. and I. Kataoka. 1999. High temperature rather than drought stress is responsible for the occurrence of double pistils in 'Satohnishiki' sweet cherry. Scientia Hort. 81:125-134.

Chalmers, D.J., P.D. Mitchell, and L. van Heek. 1981. Control of peach tree growth and productivity by regulated water supply, tree density, and summer pruning. J. Amer. Soc. Hort. Sci. 106:307-312.

Dehghanisanij, H., A. Naseri, H. Anyoji, and A.E. Eneji. 2007. Effects of deficit irrigation and fertilizer use on vegetative growth of drip irrigated cherry trees. J. Plant Nutr. 30:411-425.

Girona, J., M. Gelly, M. Mata, A. Arbonés, J. Rufat, and J. Marsal. 2005. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agr. Water Mgt. 72:97-108.

Goldhamer, D.A. and M. Viveros. 2000. Effects of preharvest irrigation cutoff durations and postharvest water deprivation on almond tree performance. Irrig. Sci. 19:125-131.

Grimplet, J., L.G. Deluc, G.R. Cramer, and J.C. Cushman. 2007. Integrating functional genomics with salinity and water deficit stress responses in wine grape – *Vitis* *vinifera*, p. 643-668 In: Jenks, M.A., Hasegawa, P.M., Jain, S.M (eds.). Advances in molecular breeding toward drought and salt tolerant crops. Springer.

Grossman, Y.L. and T.M. DeJong. 1995. Maximum fruit growth potential and seasonal patterns of resource dynamics during peach growth. Ann. Bot. 75:553-560.

Gurusinghe, S.H. and K.A. Shackel. 1995. The relation of cambial zone mechanical strength to growth and irrigation of almond [*Prunus dulcis* (Mill.) Webb.] trees. J. Amer. Soc. Hort. Sci. 120:170-176.

Intrigliolo, D.S. and J.R. Castel. 2005. Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees. J. Hort. Sci. Biotech. 80:177-182.

Lachaud, S. 1989. Participation of auxin and abscisic acid in the regulation of seasonal variations in cambial activity and xylogenesis. Trees 3:125-137.

Li, S.H., J.G. Huguet, P.G. Schoch, and P. Orlando. 1989. Response of peach tree growth and cropping to soil water deficit at various phenological stages of fruit development. J. Hort. Sci. 64:541-552.

Pérez-Pastor, A., R. Domingo, A. Torrecillas, and M.C. Ruiz-Sánchez. 2009. Response of apricot trees to deficit irrigation strategies. Irrig. Sci. 27 :231-242.

Pollack S. and A. Perez. 2002. Fruit and tree nuts outlook. Econ. Res. Serv., U.S. Dept. Agr., FTS-297. 30 Apr. 2008. <http://www.ers.usda.gov/publications/fts/mar02/fts297.pdf>.

Romero, P., P. Botia, and F. Garcia. 2004. Effects of regulated deficit irrigation under subsurface drip irrigation conditions on vegetative development and yield of mature almonds. Plant and Soil 260:169-181.

Shackel, K.A., B. Lampinen, S. Southwick, W. Olson, S. Sibbett, W. Krueger, and J. Yeager. 2000. Deficit irrigation in prunes: maintaining productivity with less water. HortScience. 35:1063-1066.

Torrecillas, A., R. Domingo, R. Galego, and M.C. Ruiz-Sánchez. 2000. Apricot tree response to withholding irrigation at different phenological periods. Scientia Hort. 85:201-215.

U.S. Department of Agriculture. 2006. Utah fruit and berry survey. 13 Oct. 2009. <www.nass.usda.gov/Statistics_by_State/Utah/Publications/Survey_Results/UTFruitSurveyPubLetter.pdf>

CHAPTER 2

REGULATED DEFICIT IRRIGATION OF 'MONTMORENCY' TART CHERRY

Introduction

The availability of water for agricultural purposes in Utah is often limiting, particularly in years with reduced winter precipitation and consequently, reduced mountain snowpack. When water resources are limiting, growers should manage their water more effectively in an attempt to maximize the water productivity. Water productivity (Fereres and Soriano, 2007) is the crop yield or net income per unit of water used in evapotranspiration (ET). Under drought conditions irrigation scheduling should be evaluated with both the reproductive and long-term health of the crop in mind. This is particularly important in perennial crops such as fruit orchards where management in one year affects the crop in the following season.

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, and improve or maintain yield and fruit quality. In RDI trials of peach and apricot, yield and fruit size were equivalent to the control when full irrigation was restored in the second rapid fruit growth phase (Girona et al., 2005; Pérez-Pastor et al., 2009; Torrecillas et al., 2000). However, RDI trials with a severe deficit, or no restoration of full irrigation prior to harvest, had a decrease in yield or fruit size (Intrigliolo and Castel, 2005; Pérez-Pastor et al., 2009;

Torrecillas et al., 2000). RDI treatments also tend to increase the concentration of soluble solids in peach and apricot fruit (Crisosto et al., 1994; Gelly et al., 2004; Pérez-Pastor et al., 2007). The objective of this work was to study the effects of different levels of RDI applied to ‘Montmorency’ tart cherry from pit hardening to harvest on yield, fruit size, and fruit quality.

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, USA (39.99° N, 111.80° W) on a Pleasant Vale loam soil with an available water holding capacity of 76 $cm \cdot m^{-1}$. The climate is semi-arid with a 30-year mean (1979-2008) annual precipitation of 486 mm, and mean precipitation during the growing season (1 March 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 and 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 a tree spacing of 4.3 x 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, one per tree, placed in the tree row midway between trees (Ultra-Jet

6900 OA; Olson Irrigation Systems, Santee, CA, USA). Each microsprinkler was rated to deliver 106 $L\cdot h^{-1}$ (at 225 kPa) and had a circular wetting pattern with a diameter of 7 m. Field measured flow rate was 98 $L\cdot h^{-1}$ at 225 kPa. A range of irrigation deficits were established by exchanging the existing nozzle for nozzles with reduced flow rates. The field measured nozzle flow rates (at 225 kPa) were 98 (commercial control) 75, 59, 46, and 28 $L\cdot h^{-1}$. The grower/cooperator used estimates of ET_c and soil water measurements to manage the frequency and length of irrigation applications, with typical applications every 4 to 10 days, for 10- to 12-h periods.

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 3 rows with 12 trees per row. The 10 central trees of the middle row were used for measurements, and the other 26 were guard trees. 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 days prior to 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 at regular intervals with midday stem water potential (Ψ_{stem}) measurements (McCutchan and Shackel, 1992). 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, USA).

Fruit quality and characteristics were determined on preharvest samples, on mechanically harvested fruit, and on commercially pitted and washed fruit. Preharvest samples were hand-picked three to four days before mechanical harvest. In total, 30 fruit were collected from three trees per plot. Fruit from the periphery of the canopy were randomly sampled at mid-tree height on both the east and west side of the row. Fruit samples were placed in plastic bags on ice, transported to the lab and refrigerated for one to two days while being evaluated. Surface color characteristics (lightness, chroma and hue) were measured on one cheek of each fruit using a portable spectrophotometer (CM-2600d; Konica Minolta Sensing, Osaka, Japan). The mass of 15 fruit were measured both before and after hand pitting. The remaining 15 whole fruit were pressed through a metal screen (0.17 cm pores) and the flesh (pulp and juice) was stored at -80 °C until soluble solids concentration (SSC) and titratable acidity were measured.

Plots were mechanically harvested using a commercial trunk shaker system (Kilby Manufacturing, Gridley, CA, USA), 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 ($7.94\ kg \cdot cm^{-1}$). Harvested yield was determined based on the accumulated fruit depths for one plot (10 trees). Fruit from 6 to 10 trees was sufficient to fill one tank, and a full tank from each plot was tracked through the packing plant to determine processing characteristics. The tanks of fruit were cooled with flowing water (4°C) for a minimum of 4 h prior to pitting, according to standard commercial practices. Subsamples of 100-fruit from each tank were used to measure SSC (hand-held refractometer), size, color, firmness, damage, and the number of stems. After the fruit were machine-pitted, another 100-fruit subsample was used to evaluate color, uniformity, frequency of blemishes, and the number of stems and pits. In 2008 the mass of undersized fruit (<9.5 mm diameter) that fell through the eliminator chain, and the mass of cull fruit removed during processing was measured. After processing, the number of 11.3 kg buckets collected from each tank of fruit was recorded. One bucket from each plot was commercially frozen and stored for a minimum of four months.

The commercially frozen samples were thawed for two days, and then juice was drained from the fruit for five minutes. The sample mass was measured before and after draining the fruit. Subsamples of the juice and drained fruit were collected and stored at -80 °C for subsequent analysis. The remaining drained fruit was spread onto metal screens and placed on racks in a commercial drying oven. In 2007 the fruit samples were dried for 2.25 h at 91 °C, and in 2008 they were dried within a range of 3 to 4 h, at 86 °C. The samples were cooled and stored at 25 °C in plastic bags for two days until they had equilibrated, then dry weight, water content, and relative humidity were measured.

The flesh from the preharvest fruit samples and the juice from the commercially frozen fruit were thawed in a 30 °C water bath, and filtered (Whatman #1). A benchtop refractometer (Abbe-3L, Bausch and Lomb) was used to measure SSC. Titratable acidity was determined on a 5 mL aliquot of the unfiltered flesh and juice samples, by titrating with 0.1 N NaOH in 95 mL of double distilled water to a final pH of 8.1. Preharvest fruit flesh, and fruit (≈ 20) and juice from the commercially frozen samples were freeze dried to determine percent dry matter (FreeZone 12, Labconco, Kansas City, MO, USA). Aliquots of juice from the commercially frozen fruit were filtered through a 0.45 µm syringe filter, and then diluted 1:4 by volume with distilled water (800 µL distilled water to 200 µL juice), before measuring absorbance at 512 nm (Özkan et al., 2002) with a transmission spectrophotometer (SpectraMax M2; Molecular Devices, Sunnyvale, CA, USA).

Treatment means were compared using PROC MIXED, ANOVA (V.9.1; SAS Institute, Inc., Cary, NC, USA). A treatment effect significant at $P \leq 0.05$ was further analyzed with the Tukey mean separation test at a significance level of $P \leq 0.05$.

Results and Discussion

Weather conditions in Spring 2008 were cooler than in 2007, resulting in delayed bloom (8 May 2008 compared to 1 Apr. 2007). From March to May the average maximum air temperature was 15.1 °C in 2008 versus 18.7 °C in 2007, compared to the 30-year mean of 16.6 °C. During the fruit ripening period (June to July) the average maximum temperature in 2008 was similar to the 30-year mean (30.1 °C and 30.3 °C respectively), while 2007 had higher temperatures (33.7 °C). During the irrigation season (1 May to 31 Aug.) precipitation (mm) was greater in 2008 than either 2007 or the 30-year mean (Table 2.1).

The RDI treatments had annual water savings from 15% to 50% in 2007 and 2008 (Table 2.2). For the commercial control, less water was applied in the 2008 irrigation season than in 2007, 451 and 526 mm, respectively (Table 2.2). However, this was offset to some degree by greater precipitation in Spring 2008 (Table 2.1). Irrigation scheduling was managed with soil water measurements and ET_c. Interestingly, irrigation applied over both seasons was closely correlated with Ψ_{stem} (Fig. A.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 to -0.78 MPa for the control. Prior to harvest in 2008, Ψ_{stem} ranged from -0.86 MPa for the control to -1.25 MPa for the most severe deficit (Fig. 2.1). 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 microspray 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.

Crop loads were moderate for both years. There were no treatment effects on mean fresh weight yield for either year (Table 2.3). The percentage of undersized fruit was slightly greater in the RDI-30 treatment (Table 2.4); however it was not enough to significantly affect packout (Table 2.3). Naor (2006) reported that as the number of fruit (crop load) increases, the effect of water stress on fruit size is enhanced. Thus, the current RDI regime was effective for the moderate crop loads of 2007 and 2008. 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 whole fruit size (grams), $r^2 = 0.19$ (Fig. A.2). This was probably due to the relatively moderate levels of both water stress and crop load, where Ψ_{stem} of tart cherry in the most severe RDI treatment was about -1.3 MPa 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 2.5). Fruit SSC also increased with the severity of RDI (Table 2.5), and was correlated with fruit dry matter content (Fig. 2.2). Chroma (color intensity) was similarly related to RDI (Table 2.6). These relationships suggest either a reduction in fruit water content (Naor, 2006) or perhaps increased dry matter accumulation for osmotic adjustment (Antunez-Barria, 2006; Hsiao et al., 1976). A similar increase in fruit dry matter content was previously reported for prune (Lampinen et al., 1995). RDI did not affect several fruit quality factors: stem number, firmness, damage, blemishes, pit removal, and surface hue and lightness (Table A.1). The effect of RDI on tart cherry dry matter content, SSC, and chroma would likely be beneficial for dried cherry processing.

The indications of this trial are that tart cherry yield and fruit quality may be safely maintained with annual irrigation savings of about 30% (RDI-60). A more severe deficit may be applied, but with the risk of increasing the number of undersized fruit. However, when control irrigation was restored to peach and apricot during stage III (Girona et al., 2005; Torrecillas et al., 2000) harvest fruit size recovered, suggesting that negative fruit size effects could be alleviated with full irrigation just prior to harvest.

Literature Cited

Antunez-Barria, A.J. 2006. The impact of deficit irrigation strategies on sweet cherry (*Prunus avium* L) physiology and spectral reflectance. Washington State Univ., PhD Diss. (UMI Microform 3252310).

Crisosto, C.H., R.S. Johnson, J.G. Luza, and G.M. Crisosto. 1994. Irrigation regimes affect fruit soluble solids concentration and rate of water loss of ‘O’Henry’ peaches. HortScience. 29:1169-1171.

Dockter, D. and P.L. Palmer. 2008. Computation of the 1982 Kimberly-Penman and the Jensen-Haise evapotranspiration equations as applied in the U.S. Bureau of Reclamation’s Pacific Northwest AgriMet Program. 23 Oct. 2009. <http://www.usbr.gov/pn/agrimet/aginfo/AgriMet%20Kimberly%20Penman%20Equation.pdf>.

Fereres, E. and M.A. Soriano. 2007. Deficit irrigation for reducing agricultural water use. J. Exp. Bot. 58:147-159.

Gelly, M., I. Recasens, J. Girona, M. Mata, A. Arbonés, J. Rufat, and J. Marsal. 2004. Effects of stage II and postharvest deficit irrigation on peach quality during maturation and after cold storage. J. Sci. Food Agr. 84:561-568.

Girona, J., M. Gelly, M. Mata, A. Arbonés, J. Rufat, and J. Marsal. 2005. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agr. Water Mgt. 72:97-108.

Hsiao, T.C., E. Acevedo, E. Fereres, and D.W. Henderson. 1976. Water stress, growth, and osmotic adjustment. Philosophical Trans. Royal Soc. London. Series B, Biol. Sci. 273:479-500.

Intrigliolo, D.S. and J.R. Castel. 2005. Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees. J. Hort Sci. Biotech. 80:177-182.

Jensen, M.E., R.D. Burman, and R.G. Allen. 1990. Evapotranspiration and irrigation water requirements. Amer. Soc. Civil Eng. Manual No. 70. New York, NY.

Lampinen, B.D., K.A. Shackel, S.M. Southwick, B. Olson, J.T. Yeager, and D. Goldhamer. 1995. Sensitivity of yield and fruit quality of French prune to water deprivation at different fruit growth stages. J. Amer. Soc. Hort. Sci. 120:139-147.

McCutchan, H. and K.A. Shackel. 1992. Stem water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). J. Amer. Soc. Hort. Sci. 117:607-611.

Moller, A.L. and R.R. Gillies. 2008. Utah Climate Center; Santaquin Chlorinator weather station. 4 Nov. 2008. <http://climate.usurf.usu.edu/index.php>.

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

Naor, A., H. Hupert, Y. Greenblat, M. Peres, A. Kaufman, and I. Klein. 2001. The response of nectarine fruit size and midday stem water potential to irrigation level in stage III and crop load. J. Amer. Soc. Hort. Sci. 126 :140-143.

Özkan, M., A. Yemenicioglu, N. Asefi, and B. Cemeroglu. 2002. Degradation kinetics of anthocaynins from sour cherry, pomegranate, and strawberry juices by hydrogen peroxide. J. Food Sci. 67:525-529.

Pérez-Pastor, A., M.C. Ruiz-Sánchez, J.A. Martínez, P.A. Nortes, F. Artés, and R. Domingo. 2007. Effect of deficit irrigation on apricot fruit quality at harvest and during storage. J. Sci. Food Agr. 87:2409-2415.

Pérez-Pastor, R. Domingo, A. Torrecillas, and M.C. Ruiz-Sánchez. 2009. Response of apricot trees to deficit irrigation strategies. Irrig. Sci. 27 :231-242.

Shackel, K.A., B. Lampinen, S. Southwick, W. Olson, S. Sibbett, W. Krueger, and J. Yeager. 2000. Deficit irrigation in prunes: maintaining productivity with less water. HortScience. 35:1063-1066.

Torrecillas, A., R. Domingo, R. Galego, and M.C. Ruiz-Sánchez. 2000. Apricot tree response to withholding irrigation at different phenological periods. Scientia Hort. 85:201-215.

Table 2.1

Weather conditions near Santaquin, Utah during 2007 and 2008 compared to the 30-year mean (1979-2008).

Month	Max air temperature (°C)			Sum precipitation (mm)			Sum ET_r (mm) [z]	
	2007	2008	mean [y]	2007	2008	mean	2007	2008
March	14.3	10.5	11.7	33.0	56.9	51.9	105	79
April	17.6	14.5	16.4	12.7	29.7	50.6	143	90
May	24.2	20.3	21.8	42.2	69.7	55.9	236	211
June	31.1	26.8	27.7	20.3	45.5	23.8	295	291
July	36.4	33.5	32.9	11.9	19.4	17.0	288	274
August	34.4	31.2	32.0	17.2	27.2	23.2	266	195
Season Total	26	23	24	137	248	222	1330	1140

[z] Kimberly-Penman equation
[y] 30 year mean (1979-2008)

Table 2.2

Seasonal irrigation applied and seasonal water savings of deficit treatments applied to tart cherry trees.

Treatment	Seasonal irrigation applied (mm)		Seasonal water savings (%)	
	2007	2008	2007	2008
C-100	526	451	0	0
RDI-77	440	382	16	15
RDI-60	377	332	28	26
RDI-47	328	293	38	35
RDI-30	263	240	50	47

Table 2.3

The effect of deficit irrigation from pit hardening to harvest on fresh weight harvest yield and packout of tart cherry.

Treatment	Harvest yield (t/ha)			Packout (% of harvest yield)		
	2007	2008	Mean	2007	2008	Mean
C-100	25.6	28.0	26.9	74.7	75.5	75.1
RDI-77	26.6	25.8	26.2	73.0	75.4	74.2
RDI-60	23.9	22.7	23.3	77.8	74.8	76.3
RDI-47	26.6	24.7	25.7	74.4	75.4	74.9
RDI-30	25.9	24.5	25.2	73.1	74.7	73.9
P-value	0.26	0.24	0.54 [z]	0.059	0.95	0.67

[z] 2007 and 2008 were not significantly different; there was no significant treatment × year interaction.
Data for harvest yield are means of six replicate plots, with 10 trees per plot. Packout was based on a 480 kg sample from each plot.

Table 2.4

The effect of deficit irrigation from pit hardening to harvest on the quantity of undersized tart cherry fruit (< 9.5 mm diameter) at packout.

Treatment	Undersized – sizing ring (% of 100-fruit subsample)		Undersized – eliminator chain (% of harvest tank)
	2007	2008	2008
C-100	0.2	0.3	0.9 B[z]
RDI-77	0.5	1.0	0.9 B
RDI-60	0.5	0.3	1.0 B
RDI-47	0.3	0.5	1.4 A
RDI-30	1.7	1.8	2.0 A
P-value	0.19	0.063	< 0.0001

[z] Mean separation by Tukey-Kramer at $P < 0.05$.
Harvest tanks contained a mean of 480 kg

Table 2.5

The effect of deficit irrigation from pit hardening to harvest on the dry matter content and soluble solids concentration (SSC) of samples of fruit flesh collected pre-harvest.

Treatment	Dry matter content (%)				SSC (%)			
	2007		2008		2007		2008	
C-100	14.4	B	13.8	B	14.1	B	13.3	B
RDI-77	14.3	B	13.8	B	14.0	B	13.4	B
RDI-60	14.6	AB	14.1	B	14.3	B	13.5	B
RDI-47	14.7	AB	14.1	AB	14.4	AB	13.7	AB
RDI-30	15.3	A	14.8	A	14.9	A	14.3	A
P-value	0.0074		0.0017		0.0009		0.0003	

[z] Mean separation by Tukey-Kramer at $P < 0.05$.
Data are means of six replicate plots, with three trees sampled per plot, and one 15-fruit sample per tree.

Table 2.6

The effect of deficit irrigation from pit hardening to harvest on the surface color intensity (chroma) of hand harvested tart cherry fruit, and on the absorbance of juice from commercially harvested and processed fruit.

Treatment	Chroma		Absorbance (%, at 512 nm)	
	2007	2008	2007	2008
C-100	21.9 C[z]	24.6	32.9 B	43.8
RDI-77	22.3 BC	24.4	34.0 AB	45.1
RDI-60	22.7 ABC	24.8	32.5 B	44.2
RDI-47	23.1 AB	24.3	34.1 AB	45.7
RDI-30	23.3 A	25.1	38.0 A	50.1
P-value	0.0001	0.14	0.0079	0.057

[z] Mean separation by Tukey-Kramer at $P < 0.05$.
Chroma data are means of six replicate plots, with three trees sampled per plot and 20 fruit per tree.
Data for absorbance are means of six replicate plots.

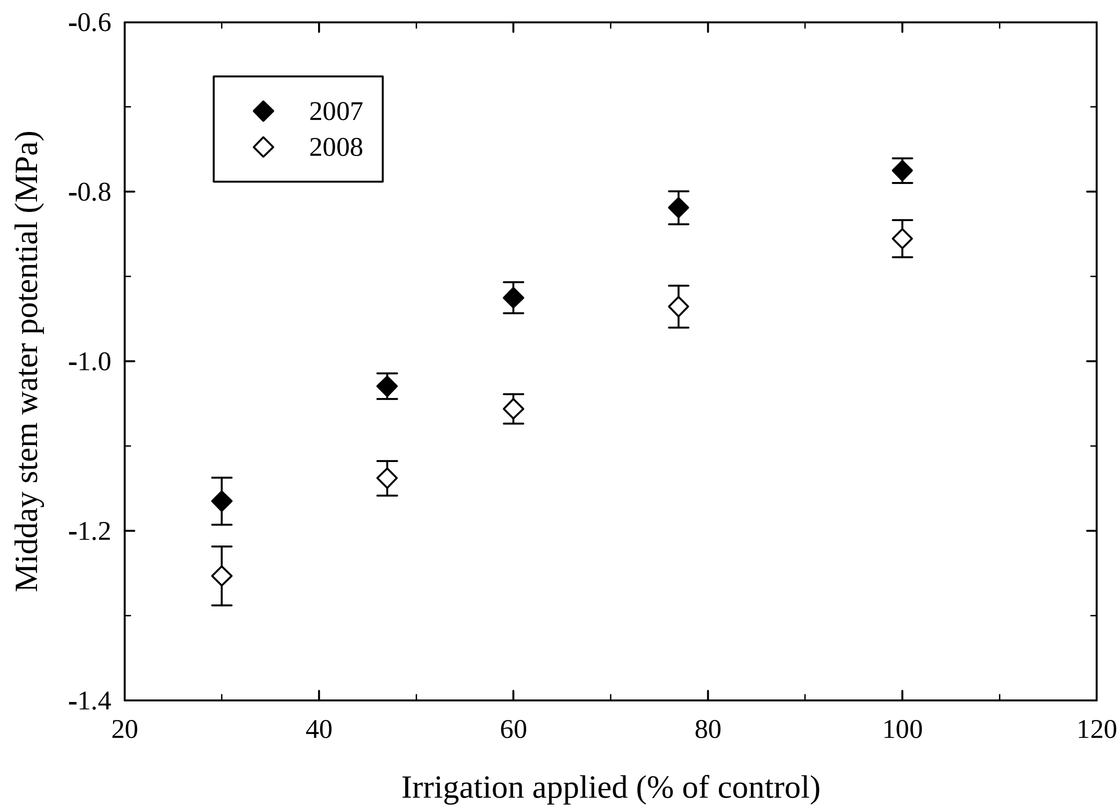

Fig. 2.1 The effect of deficit irrigation from pit hardening to harvest on tart cherry tree midday stem water potential (Ψ_{stem}) prior to harvest (9 and 2days prior to harvest in 2007 and 2008, respectively). Data are the mean of six replicate plots, with three trees sampled per plot. The vertical bars indicate the standard error of the mean.

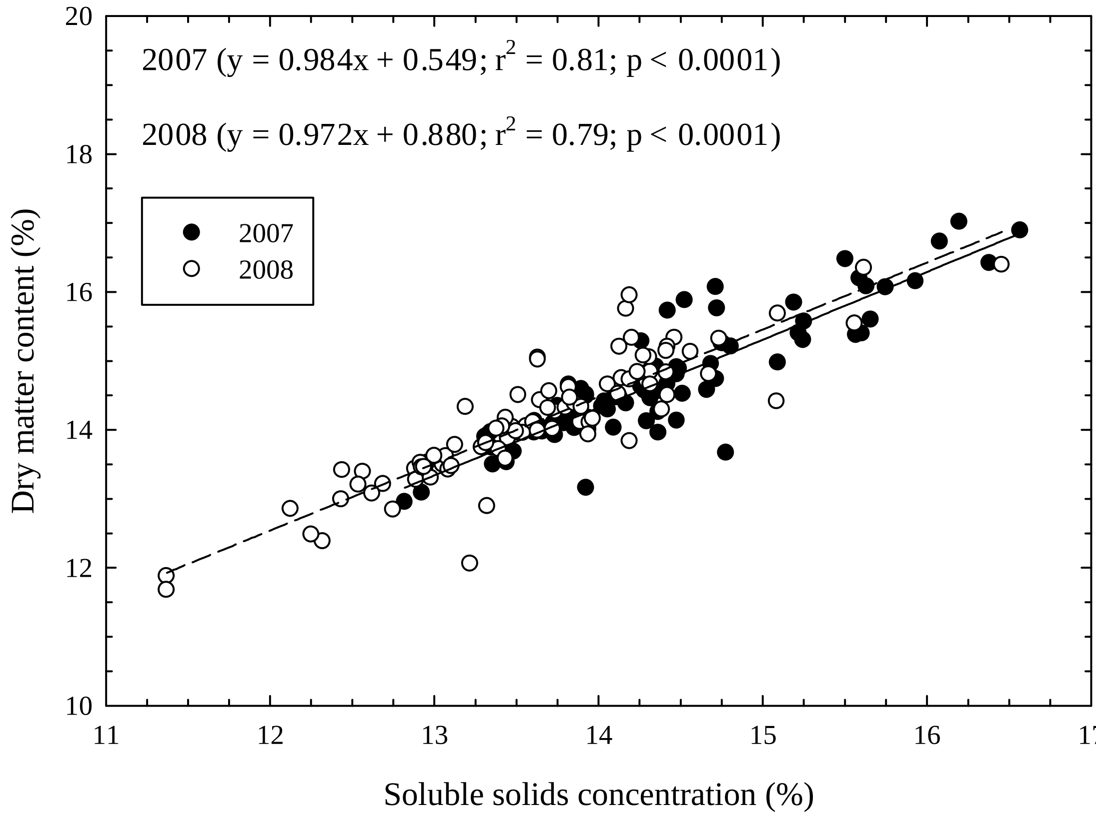

Fig. 2.2 The relationship between soluble solids concentration (SSC) and dry matter content of fruit from tart cherry trees under deficit irrigation regimes from pit hardening to harvest. The dotted regression line corresponds to 2008, and the solid line to 2007.

CHAPTER 3

INITIAL OBSERVATIONS OF TREE HEALTH

Introduction

Regulated deficit irrigation (RDI) is often used to manage vegetative growth for the purpose of improving light penetration in the canopy and reducing pruning requirements. It has also been suggested that a dry down period or drought stress before harvest will reduce bark damage in fruit crops that are mechanically harvested with a trunk shaker (Brown et al., 1984). Bark damage is often the infection court of pathogens (Fridley et al., 1970) and insects. Accumulated damage also reduces the quantity of vascular tissue which can reduce nutrient and water flow (Brown et al., 1982). In the U.S., tart cherry trees are mechanically harvested using trunk shaking equipment, which often damages the bark (Fig. 3.1). Accumulated damage over multiple seasons reduces the productivity and shortens the lifespan of the tree (Brown et al., 1982). RDI may be a strategy to minimize this trunk injury.

The sensitivity of cambial growth to environmental conditions, such as drought stress has been investigated through dendrochronological and physiological studies (Akkemik et al., 2006; Hsiao et al., 1976; Wimmer et al., 2002). Akkemik et al. (2006) studied the growth of five dominant oak trees, and found a correlation between trunk growth (10-day period) and soil water content (average from 0 to 70 cm depth). The correlation was 0.96 in a dry year and 0.49 in a humid wet year. Another study correlating growth and wood density of eucalyptus with soil water potential (Wimmer et al., 2002) found reduced growth in drought stressed trees, and a decrease in wood density after the tree was released from water stress. Preharvest midday stem water potentials of -1.2 to -2.0 MPa in peach (7-year-old) and plum (4-year-old) resulted in a significant reduction in trunk cross-sectional growth (15%) by the third or fourth year of the trial (Intrigliolo and Castel, 2005; Girona et al., 2005). Likewise, in 13-year-old almond trees with RDI during kernel-filling stage (20% ET_c) and postharvest (50% ET_c) the trunk growth rate was significantly less than the control (Romero et al., 2004). However, irrigation cutoffs during flowering to fruit set, stage I and II, stage III, early postharvest, or late postharvest did not affect the trunk growth rate of 9-year-old apricot trees (Torrecillas et al., 2000). Similarly, Pérez-Pastor et al. (2009) found no significant reduction in trunk growth of apricot with 40% ET_c during flowering, stage I, stage II, or late postharvest.

The hypothesis that cambial activity is related to bark/wood adhesion strength was developed through forestry studies on debarking (Einspahr et al., 1971; Wilcox, 1962). Shear strength measurements at different times throughout the season were carried out on several species with the overall conclusion that bark/wood adhesion was lowest when the cambium was either actively dividing or when the phloem cells were differentiating in the spring around bud break (Einspahr et al., 1971). The average length of the active cambium season for birch, aspen, oak and maple was 80 days, beginning in April to May and ending in July to August, with 111 days for a vigorous stand of oak on a moist site (Einspahr et al., 1971). Wilcox (1962) reported a correlation of the cyclic growth of the cambium with leaf-renewal and bark-peeling resistance. However, an orchard study on bark shear strength of 7-year-old almond trees showed no correlation between cambial strength and tree water status or tree growth rate, as well as no influence by irrigation deficits on the length of the active cambial season (Gurusinghe and Shackel, 1995). This lack of a response may be due to variations in cambial growth rate within a season.

The fruiting cycle of orchard trees is a perennial process where stress factors in one season can influence flower bud initiation and subsequent fruiting in the following season. Drought stress of prune during stage II resulted in an increase of flowers the following year (Lampinen et al., 1995). In apricot, RDI during early postharvest resulted in an increase in initial fruit drop during the following season. However, irrigation cutoffs during flowering to fruit set, stage I and II, stage III, or late postharvest had no effect on subsequent fruit set (Torrecillas et al., 2000). In plum, flowering and fruit set were not affected by either preharvest or postharvest irrigation regimes (Intrigliolo and Castel, 2005).

In addition to flower number and viability, stress may influence flower formation. Patten et al. (1989) found increased incidence of double or “twin” fruit resulting from drought stress of peach. Double fruit occur when two or more carpels within a single flower develop and fuse together. In sweet cherry, Beppu and Kataoka (1999) reported that doubling was a function of bud temperature and was not affected by drought stress.

The objective of this work was to study the effects of different levels of RDI applied to ‘Montmorency’ tart cherry from pit hardening to harvest on tree health, including trunk injury susceptibility, return bloom, and fruit doubling.

Materials and Methods

Experimental Plot

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, Utah, USA (39.99° N, 111.80° W). Orchard rows were oriented north to south, with a tree spacing of 4.3 x 5.5 m. Irrigation was applied with microsprinklers, one per tree, placed in the tree row midway between trees (Ultra-Jet 6900 OA; Olson Irrigation Systems, Santee, CA, USA). Each microsprinkler was rated to deliver 106 $L \cdot h^{-1}$ (at 225 kPa) and had a circular wetting pattern with a diameter of 7 m. Field measured flow rate was 98 $L \cdot h^{-1}$ at 225 kPa. A range of irrigation deficits were established by exchanging the control nozzle for nozzles with reduced flow rates. The field measured nozzle flow rates (at 225 kPa) were 98 (commercial control) 75, 59, 46, and 28 $L \cdot h^{-1}$. The grower/cooperator used estimates of ET_c and soil water measurements to manage the frequency and length of irrigation applications, with typical applications every 4 to 10 days, for 10- to 12-h periods.

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 3 rows with 12 trees per row. The 10 central trees of the middle row were used for measurements, and the other 26 were guard trees. Irrigation treatments were imposed beginning at the pit hardening stage of fruit development and continued through harvest. Irrigation was discontinued in the orchard from 8 to 14 days prior to harvest to decrease soil compaction by the harvest equipment. Microsprinkler nozzles in the RDI treatment plots 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.

Injury Susceptibility

The effect of RDI on the susceptibility of trunk bark to injury was quantified through several methods. These included postharvest measurements of visible trunk damage, ratings of harvest ease and efficiency, and through several destructive measures of bark adhesion.

Visible Bark Damage

After harvest in 2007 and 2008 the length of bark splits was recorded. Splits were categorized as either a new wound or an extension of an old wound. In 2007 old wounds were characterized according to their severity, with a rating from one to three. Also, the length of gum dripping from the wounds was recorded in 2007, a month following harvest (24 July to 17 Sep.).

Harvest Ease and Efficiency

In 2007 during mechanical harvest, three of the blocks were rated for ease of harvest, from 1 to 10 (difficult to easy) by the shaker operator, considering both the force and duration of the shaking process. The harvest efficiency was estimated by rating the amount of cherries remaining on the tree after harvest on a scale of 1 to 5, (many to few).

Bark Torque Strength

In 2008 the torque strength of the bark was measured before harvest for two replicate blocks. The torque strength on the east and west sides of the trunk was measured at 1.5 m above the ground, at the same height but opposite sides from where the trunk shaker clamps are attached. A 17-mm diameter cork borer was pushed into the bark just past the cambium, and then removed as a wooden dowel was pressed against the bark inside the cork borer to keep the bark core intact. Needles (3 to 4) and a Phillips-head screw were epoxied into a 19.1 mm (¾ inch) nut. The needles were pushed into the bark about 0.5 cm deep. Then a digital torque tester (DSD-4; Imada, Northbrook, IL, USA) with a 6.4 mm (¼ inch) Phillips head attachment, was used to rotate the head clockwise, and then record the maximum torque required to free the bark core from the wood ($N \cdot cm^{-1}$)

Shear Force Measurements

Duchesne and Nylinder (1996) studied cambial strength in a debarking study of Norway spruce and Scots pine, using dehydrated or hydrated stored logs. An electric drill fitted with a core drill bit was used to remove 12-mm-diameter cores from the trunk. The cores were then placed in a sample holder. A clamp with a circular hole was placed around the bark, and the core was adjusted vertically to place the bottom of the clamp at the cambial layer. Horizontal pressure was applied and measured with a force gauge until the bark sheared from the core sample.

In Summer 2007 bark cores were successfully removed from apple trees with a core drill bit and a battery powered drill. However, the tart cherry trees were in the “bark slipping" stage and the bark sheared before the coring bit could reach the cambium, indicating that tart cherry bark is too fragile for this method. Adjusting the method, a small diameter branch was cut from a tart cherry tree and brought to the lab, where segments 2 to 3 cm in length were cut from the branch with a band saw. A drill chuck mounted on a steel plate was used to stabilize the sample, and the plate was attached to the force tester (Instron 5542; Norwood, MA, USA). Longitudinal shear strength of the cambium was determined by separating the bark from the wood with a thin blunt edged blade. The blade was sanded flat from a decapitated bolt, and the bolt was attached to the force tester through a hole drilled in the top of the bolt. The flat blade was positioned to shear the bark at the cambium.

Return Bloom and Doubling

At the beginning of May 2008, individual branch counts of blossoms were recorded from four branches per tree, 10 trees per plot, and six replicate plots. Branches were located approximately 1.5 m above the ground, with one branch in each compass direction. The branch cross-sectional area ranged from 0.2 to 3.2 cm^2, and return bloom was analyzed as number of blossoms per branch cross-sectional area. In May 2009 blossom counts were made on one branch per tree per plot, and six replicate plots, with branch cross-sectional area ranging from 0.4 to 5.0 cm^2.

The occurrence of fruit doubles was recorded in 2008 during the preharvest sample collection from three trees per plot, and six replicate plots. The presence of double fruit within a 1.2 x 1.4 m^2 window, on both the east and west side of the tree, was noted during fruit sampling.

Results and Discussion

Some bark splitting was observed across all treatments (Fig. 3.2). In some cases visible splits were the extensions or re-injury of previous damage, whereas other visible cracks were new injuries. The statistical assumptions of normality of sampling distribution and equal variance were not met for the analysis of bark split lengths. However, there was a trend of increasing length of bark splits as the amount of irrigation applied increased (Fig. 3.3). A similar non-significant trend was reported in 14-year-old almond trees where bark injury was inversely related to the length of irrigation cutoff (Goldhamer and Viveros, 2000). However, the affect of the irrigation cutoffs on almond trunk cross-sectional growth was only significantly lower than the control in the most severe irrigation cutoff (57 days preharvest versus 8 days). Another RDI almond trial (Romero et al., 2004) did not have significant reductions in trunk growth rate compared to the control when RDI was applied during the kernel-filling stage. Thus, RDI or irrigation cutoffs from the kernel-filling stage until harvest (2 months) may not be as effective at reducing vegetative growth. Similarly in apricot (9- and 12-year-old), RDI applied during stage I and II, or both stage II and 2 months after harvest did not significantly reduce trunk-cross sectional area (Pérez-Pastor et al., 2009; Torrecillas et al., 2000). Shoot growth of apricot is 85% completed when stage I begins, with another stage of shoot growth occurring after harvest (Torrecillas et al., 2000). The authors hypothesized that trunk growth was unaffected due to the maturity of the apricot trees. However, it may also be related to RDI application during a less active vegetative stage, or to the moderate level of drought stress.

Trunk injury was estimated as the length of visible bark splits, and although it is an indirect measure of bark strength, it may not represent actual changes in cambial activity and bark strength. Attempts at directly measuring bark strength were not repeatable. For example bark torque strength measurements were complicated by repeated failure of the needles, or epoxy. Average torque measurements ranged from 20.0 to 24.5 N cm, and were not correlated with irrigation treatment (Figure A.3). Measurements of tangential bark shear force were unsuccessful due to the inability of removing cores with intact bark from the branch or bole. Finally, trial measurements of bark shear force on intact branches were complicated by uneven surfaces on the branch segments.

Ease of harvest as rated by the shaker operator showed treatment differences (Table 3.1) but these differences were not correlated with RDI level. Ratings were not taken in 2008, as all of the plots were harvested predawn, and operators could not make ratings in the dark. Estimates of fruit remaining after harvest also showed treatment differences in both years, but again the differences were not correlated with the level of RDI (Table 3.1).

Return bloom after one or two seasons of RDI did not differ among treatments (Fig. 3.4). The frequency of doubled fruits was extremely low in both seasons. In 2008, only 17 double fruit were found in the 90 trees observed, and there was no correlation with RDI severity.

These results indicate that RDI from pit hardening to harvest did not affect return bloom, and did not increase the susceptibility of the trees to bark injury. In fact, there was some indication that bark damage could be reduced with the application of RDI. Any reduction of bark injury would be beneficial for the tart cherry industry.

Literature Cited

Akkemik, Ü., H. Çinar Yilmaz, and O. Sevgi. 2006. Cambial activity of the Sessile Oak (*Quercus petraea*) in Belgrade Forest, İstanbul. Turk J. Agric. For. 30:429-438.

Beppu K. and I. Kataoka. 1999. High temperature rather than drought stress is responsible for the occurrence of double pistils in ‘Satohnishiki’ sweet cherry. Scientia Hort. 81:125-134.

Brown, G.K., J.R. Frahm, and R.L. Ledebuhr. 1982. Bark damage when trunk shaking cherry trees. Amer. Soc. Agr. Eng. 82:1577.

Brown, G. K., J.R. Frahm, L.J. Segerlind, and B.F. Cargill. 1984. Shaker damage to cherry bark: Causes and cures, p. 364–371. Proc. Intl. Symp. Fruit, Nut, & Vegetable Harvesting Mechanization, Bet Dagan, Israel, 5-12 Oct. 1983. Amer. Soc. Agr. Eng. Publ. 5-84.

Duchesne, I. and M. Nylinder. 1996. Measurement of the bark/wood shear strength: Practical methods to evaluate debarking resistance of Norway spruce and Scots pine pulpwood. Forest Prod. J. 46:57-62.

Einspahr, D.W., J.D. Hankey, W.A. Wink, M.K. Benson, and J.W. Swanson. 1971. Wood/bark adhesion and methods of reducing adhesion in hardwood species. 11 June 1971. Appleton, Wisconsin; the Institute, Georgia Institute of Technology. Project 2929; report 2. 12 Nov. 2009. <http://hdl.handle.net/1853/1426>.

Fridley, R.B., G.K. Brown, and P.A. Adrian. 1970. Strength characteristics of fruit tree bark. Hilgardia 40:205-222.

Girona, J., M. Gelly, M. Mata, A. Arbonés, J. Rufat and J. Marsal. 2005. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agr. Water Mgt. 72:97-108.

Goldhamer, D.A. and M. Viveros. 2000. Effects of preharvest irrigation cutoff durations and postharvest water deprivation on almond tree performance. Irrig. Sci. 19:125-131.

Gurusinghe, S.H. and K.A. Shackel. 1995. The relation of cambial zone mechanical strength to growth and irrigation of almond [*Prunus dulcis* (Mill.) Webb.] trees. J. Amer. Soc. Hort. Sci. 120:170-176.

Hsiao, T.C., E. Acevedo, E. Fereres, and D.W. Henderson. 1976. Water stress, growth, and osmotic adjustment. Philosophical Trans. Royal Soc. London. Series B, Biol. Sci. 273:479-500.

Intrigliolo, D.S. and J.R. Castel. 2005. Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees. J. Hort Sci. Biotech. 80:177-182.

Lampinen, B.D., K.A. Shackel, S.M. Southwick, B. Olson, J.T. Yeager, and D. Goldhamer. 1995. Sensitivity of yield and fruit quality of French prune to water deprivation at different fruit growth stages. J. Amer. Soc. Hort. Sci. 120:139-147.

Patten, K., G. Nimr, and E. Neuendorff. 1989. Fruit doubling of peaches as affected by water stress. Acta Hort. 254:319-322.

Pérez-Pastor, R. Domingo, A. Torrecillas, and M.C. Ruiz-Sánchez. 2009. Response of apricot trees to deficit irrigation strategies. Irrig. Sci. 27 :231-242.

Romero, P., P. Botia, and F. Garcia. 2004. Effects of regulated deficit irrigation under subsurface drip irrigation conditions on vegetative development and yield of mature almonds. Plant and Soil. 260:169-181.

Torrecillas, A., R. Domingo, R. Galego, and M.C. Ruiz-Sánchez. 2000. Apricot tree response to withholding irrigation at different phenological periods. Scientia Hort. 85:201-215.

Wilcox, H. 1962. Cambial growth characteristics, p. 61-64. In: T.T. Kozlowski (ed.). Tree growth. Ronald Press, New York.

Wimmer, R., G.M. Downes, and R. Evans. 2002. High-resolution analysis of radial growth and wood density in *Eucalyptus nitens*, grown under different irrigation regimes. Ann. For. Sci. 59:519-524.

Table 3.1

The effect of deficit irrigation from pit hardening to harvest on the mechanical harvest ratings of tart cherry trees. Ease of harvest was an operator rating (1=most difficult, 10=easiest) based on duration and force of shaking. Harvest efficiency was based on a visual rating of remaining fruit (1 = most, 5 = least).

Treatment	Ease of harvest (1 to 10)	Harvest efficiency (1 to 5)	
	2007	2007 [y]	2008 [y]
C-100	4.7 B [z]	3.9 B	4.4 AB
RDI-77	5.2 B	4.5 A	4.7 A
RDI-60	6.9 A	4.0 B	4.3 AB
RDI-47	5.5 B	4.0 B	4.4 AB
RDI-30	5.8 AB	4.1 B	4.2 B
P-value	0.001	0.0005	0.016

[z] Means separated at $P < 0.05$ using Tukey-Kramer test
[y] log transformation
Data for ease of harvest are the mean of three replicate plots. Data for harvest efficiency are the mean of six replicate plots, and 10 trees per plot.

Fig. 3.1 An example of accumulated bark damage from mechanical harvest of tart cherry trees. Pictured is a 14 year-old-tree from a commercial orchard in Santaquin, Utah.

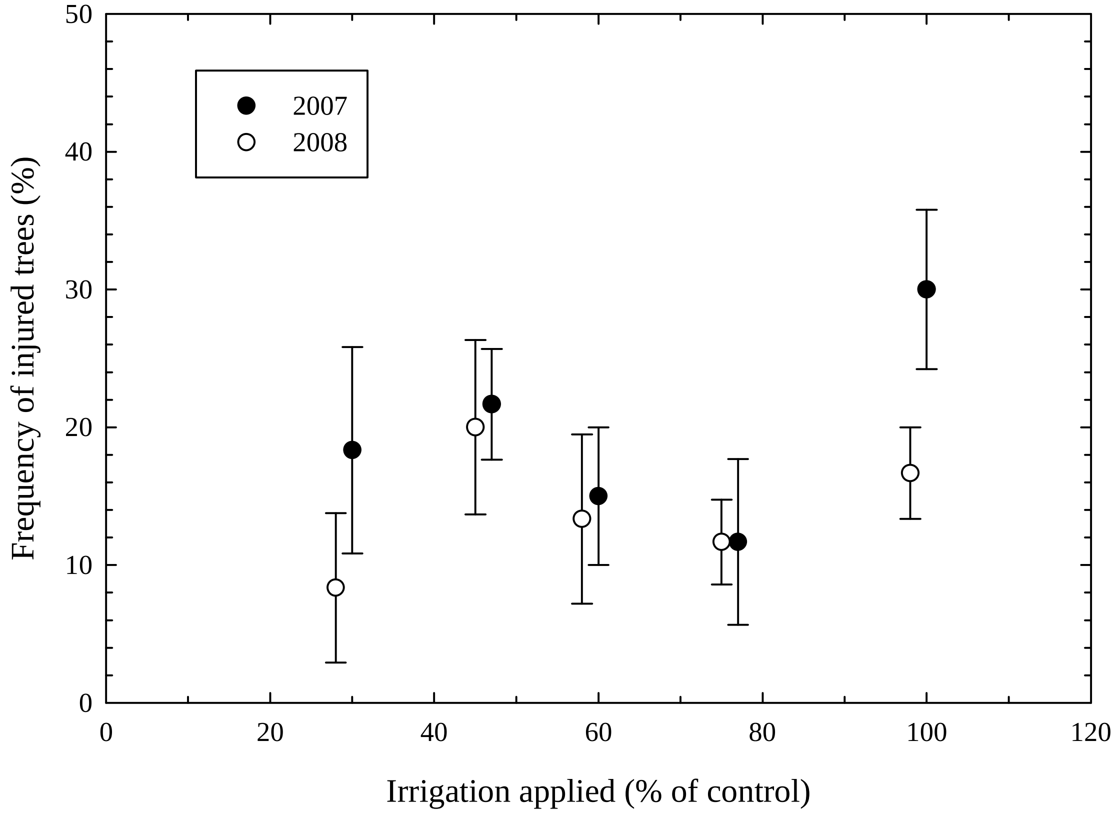

Fig. 3.2 The effect of deficit irrigation from pit hardening to harvest on the number of trees with bark splits after mechanical harvest. Each point is the mean of six replicate plots, and 10 trees per plot.

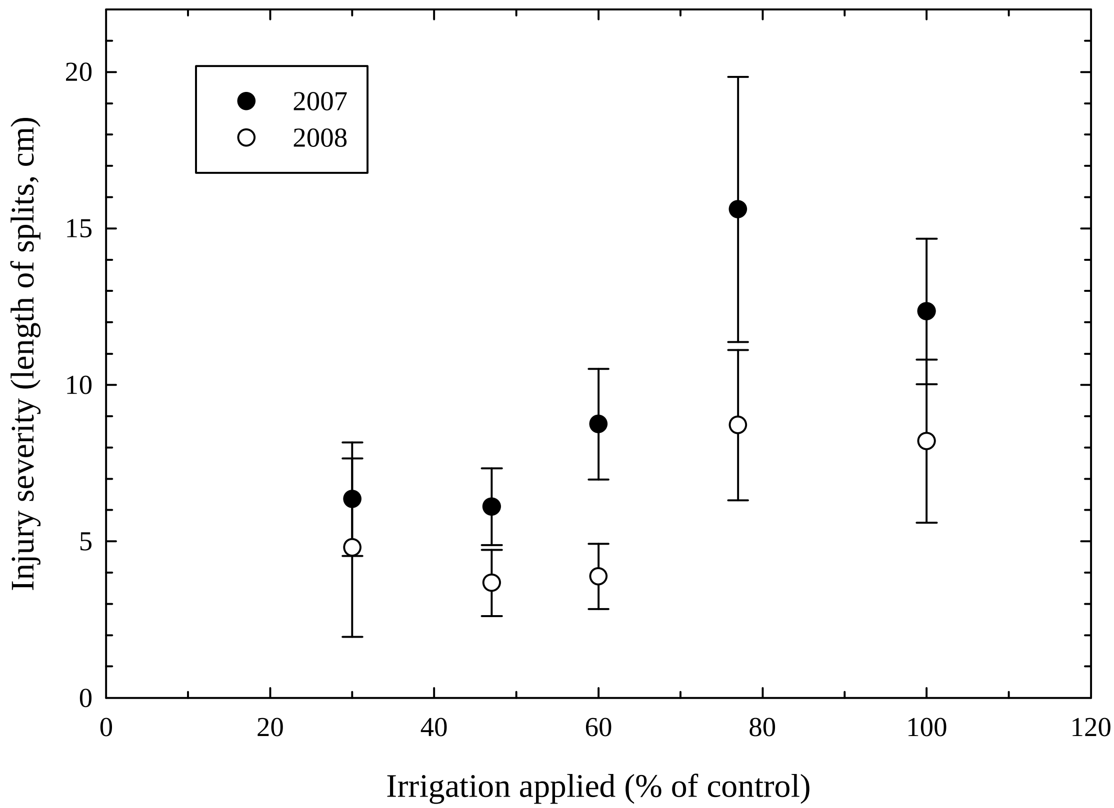

Fig. 3.3 The effect of deficit irrigation from pit hardening to harvest on the average length of tart cherry tree bark splits (cm) after mechanical harvest. Each point is the mean of six replicate plots, and observed injured trees out of 10 per plot.

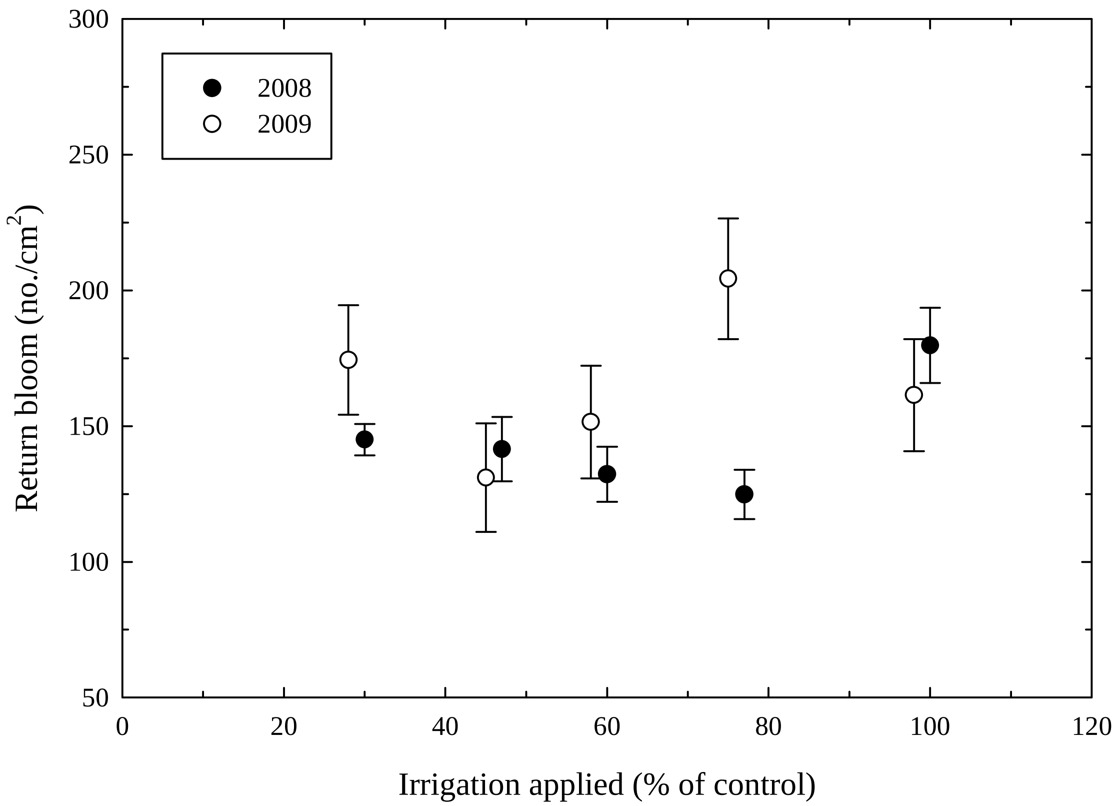

Fig. 3.4 The effect of deficit irrigation from pit hardening to harvest on return bloom of tart cherry trees. Return bloom was analyzed as the number of blossoms per branch cross-sectional area. Each point in 2008 is the mean of six replicate plots, three trees per plot, and four branches per tree. Each point in 2009 is the mean of six replicate plots, one tree per plot, and one branch per tree.

CHAPTER 4

SUMMARY AND CONCLUSIONS

RDI treatments applied to 'Montmorency' tart cherry trees resulted in moderate levels of water stress when compared to reported thresholds for other stone fruit crops (Antunez-Barria, 2006; Girona et al., 2005; Intrigliolo and Castel, 2005; Shackel et al., 2000). The stress applied in the RDI treatments did not decrease yield, and any reductions in fruit size did not affect the final packout in either 2007 or 2008. The amount of water that might be saved in a season ranged from 15% to 50% of seasonal irrigation. With an average seasonal irrigation application of 500 mm water and 1276 hectares of tart cherry trees in Utah (U.S. Department of Agriculture, 2006), estimated water savings for the Utah industry would be 95 to 320 hectare-meters of water (780 to 2600 acre-feet of water) per year.

Despite this savings in water, there was no reduction in crop yield. Fruit size was affected, but not sufficient to affect packout. Further, trends in fruit quality indicated that RDI increased fruit dry matter content, SSC and chroma. These changes could improve the quality of dried product, a benefit to the Utah industry.

Preliminary research on tree health indicated that the RDI treatments didn't affect return bloom, and didn't increase the susceptibility of the trees to bark injury. In fact, there were some indications that bark damage could be reduced with the application of RDI. With better testing procedures of bark strength, tree growth, and tree health, the effects of RDI could be more clearly defined in tart cherry. Additional research is also needed to monitor the long-term effects of RDI on orchard health and productivity. The life span of a cherry orchard decreased from 30 to 20 years with the introduction of mechanical harvesting (Brown et al., 1984). So, any progress on reducing trunk damage from mechanical harvesting would be beneficial towards improving orchard longevity and profitability.

In order for growers to administer RDI treatments safely and effectively, management strategies need to be outlined, such as the correct use of tree water stress sensors, improved soil moisture sensing capabilities, and general irrigation scheduling from ET_r values and K_c (crop coefficient) values for water stressed crops. The narrow window for midday stem water potential measurements (a few hours around solar noon) is impractical for commercial measurements. Current research on leaf spectral reflectance has shown possible application in orchard management (Antunez-Barria, 2006) as well as having measurements that are closely correlated with midday stem water potential. Any tree water status sensor used for orchard management should have calibrated crop stress thresholds to safely manage yield and tree health. The sensor should also be sensitive to tree stress several days before any crop damage would occur.

The results for RDI of tart cherry in Utah have been promising, and deserve further investigation, considering the improved fruit quality for processing without a compromise in yield, the conservation of limited water resources, and the possible improvement in tree health.

Literature Cited

Antunez-Barria, A.J. 2006. The impact of deficit irrigation strategies on sweet cherry (*Prunus avium* L) physiology and spectral reflectance. Washington State Univ., PhD Diss. (UMI Microform 3252310).

Brown, G. K., J.R. Frahm, L.J. Segerlind, and B.F. Cargill. 1984. Shaker damage to cherry bark: Causes and cures, p. 364–371. Proc. Intl. Symp. Fruit, Nut, & Vegetable Harvesting Mechanization, Bet Dagan, Israel, 5-12 Oct. 1983. Amer. Soc. Agr. Eng. Publ. 5-84.

Girona, J., M. Gelly, M. Mata, A. Arbonés, J. Rufat and J. Marsal. 2005. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agr. Water Mgt. 72:97-108.

Intrigliolo, D.S. and J.R. Castel. 2005. Effects of regulated deficit irrigation on growth and yield of young Japanese plum trees. J. Hort Sci. Biotech. 80:177-182.

Shackel, K.A., B. Lampinen, S. Southwick, W. Olson, S. Sibbett, W. Krueger, and J. Yeager. 2000. Deficit irrigation in prunes: maintaining productivity with less water. HortScience. 35:1063-1066.

U.S. Department of Agriculture. 2006. Utah fruit and berry survey. 13 Oct. 2009. <www.nass.usda.gov/Statistics_by_State/Utah/Publications/Survey_Results/UTFruitSurveyPubLetter.pdf>

APPENDIX

Tables and Figures

Table A.1 Deficit irrigation from pit hardening to harvest did not affect several tart cherry fruit quality factors: stem number (before and during packout), firmness, damage, blemishes, pit removal failure, and surface hue and lightness. The descriptive statistics and SAS output are shown below.

Stems 2007							Stems 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	6	4.83	2.71	1.11	4.00	56.2	6	5.33	2.42	0.99	5.00	45.4
77	6	5.83	3.54	1.45	6.00	60.8	6	4.00	2.45	1.00	3.00	61.2
60	6	8.00	4.69	1.91	7.00	58.6	6	4.67	2.16	0.88	4.50	46.3
47	6	4.67	2.80	1.15	4.00	60.1	6	6.83	3.66	1.49	6.50	53.5
29	6	7.67	3.50	1.43	8.00	45.7	6	9.17	4.54	1.85	8.50	49.5

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	20	1.52	0.234	4	20	2.13	0.114
block	5	20	2.47	0.068	5	20	0.23	0.943

Soft (%) 2007							Soft (%) 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	6	2.67	1.03	0.422	3.00	38.7	6	1.50	1.05	0.428	1.50	69.9
77	6	1.67	1.03	0.422	2.00	62.0	6	1.33	0.52	0.211	1.00	38.7
60	6	4.17	2.64	1.078	5.00	63.3	6	0.67	0.52	0.211	1.00	77.5
47	6	2.17	1.72	0.703	2.00	79.5	6	1.50	0.84	0.342	1.00	55.8
29	6	2.33	1.51	0.615	2.00	64.5	6	1.00	0.63	0.258	1.00	63.2

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	20	1.76	0.177	4	20	1.39	0.273
block	5	20	0.68	0.644	5	20	0.85	0.53

Blemish 2007							Blemish 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	6	1.67	0.82	0.333	1.50	49	6	4.67	1.75	0.71	5.50	37.5
77	6	0.83	0.98	0.401	0.50	118	6	5.00	2.37	0.97	4.50	47.3
60	6	1.83	1.17	0.477	1.50	64	6	4.50	0.55	0.22	4.50	12.2
47	6	1.17	0.41	0.167	1.00	35	6	5.83	2.40	0.98	6.50	41.2
29	6	2.00	0.89	0.365	2.00	45	6	6.17	3.19	1.30	5.00	51.7

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	20	1.65	0.2	4	20	0.64	0.641
block	5	20	0.63	0.679	5	20	0.94	0.475

	Serious blemish 2007						Serious blemish 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	6	0.00	0.00	0.000	0.00	.	6	0.00	0.00	0.000	0.00	.
77	6	0.67	0.52	0.211	1.00	77	6	0.67	0.52	0.211	1.00	77
60	6	0.33	0.52	0.211	0.00	155	6	0.33	0.52	0.211	0.00	155
47	6	0.17	0.41	0.167	0.00	245	6	0.17	0.41	0.167	0.00	245
29	6	0.33	0.52	0.211	0.00	155	6	0.33	0.52	0.211	0.00	155

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	20	1.96	0.139	4	20	1.96	0.139
block	5	20	1.18	0.354	5	20	1.18	0.354

	Packout stems 2007						Packout stems 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	6	1.33	0.52	0.211	1.00	39	6	0.00	0.00	0.000	0.00	.
77	6	0.50	0.55	0.224	0.50	110	6	0.17	0.41	0.167	0.00	245
60	6	1.50	1.05	0.428	1.50	70	6	0.00	0.00	0.000	0.00	.
47	6	0.67	0.82	0.333	0.50	122	6	0.00	0.00	0.000	0.00	.
29	6	1.50	1.05	0.428	1.50	70	6	0.17	0.41	0.167	0.00	245

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	20	1.97	0.139	4	20	1	0.431
block	5	20	0.88	0.511	5	20	2.67	0.053

	Pit 2007						Pit 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	6	0	0	0	0	.	6	0	0	0	0	.
77	6	0	0	0	0	.	6	0.167	0.41	0.17	0	245
60	6	0.833	2.041	0.833	0	245	6	0	0	0	0	.
47	6	0.833	2.041	0.833	0	245	6	0	0	0	0	.
29	6	0	0	0	0	.	6	0.333	0.52	0.21	0	155

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	20	0.71	0.5919	4	20	1.43	0.261
block	5	20	0.76	0.5878	5	20	0.64	0.6699

Lightness 2007							Lightness 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	18	28.5	0.74	0.173	28.5	2.58	15	28.2	0.99	0.256	28.0	3.52
77	18	28.3	1.04	0.246	28.6	3.68	15	28.7	0.70	0.180	28.6	2.43
60	18	28.5	0.90	0.213	28.4	3.17	15	28.4	0.94	0.243	28.4	3.31
47	18	28.5	0.84	0.198	28.3	2.94	15	28.5	0.65	0.168	28.6	2.28
29	18	28.4	0.87	0.205	28.8	3.06	15	28.6	0.43	0.111	28.6	1.51

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	80	0.17	0.9511	4	66	1.05	0.3897
block	5	80	0	1	4	66	0	1

Hue 2007							Hue 2008					
irr	n	mean	SD	SE	median	CV	n	mean	SD	SE	median	CV
100	18	19.6	0.76	0.178	19.7	3.87	15	20.9	0.89	0.230	20.8	4.26
77	18	19.7	0.70	0.166	19.9	3.58	15	20.8	0.62	0.159	20.6	2.96
60	18	19.9	0.68	0.160	20.0	3.40	15	20.8	0.90	0.233	21.1	4.33
47	18	20.0	0.83	0.196	20.1	4.16	15	20.7	0.64	0.165	20.9	3.10
29	18	19.9	0.78	0.183	20.1	3.90	15	20.9	0.99	0.256	20.7	4.75

Type 3 Tests of Fixed Effects								
Effect	Num DF	Den DF	F Value	Pr > F	Num DF	Den DF	F Value	Pr > F
irr	4	80	1.09	0.3652	4	66	0.18	0.9461
block	5	80	0	1	4	66	0	1

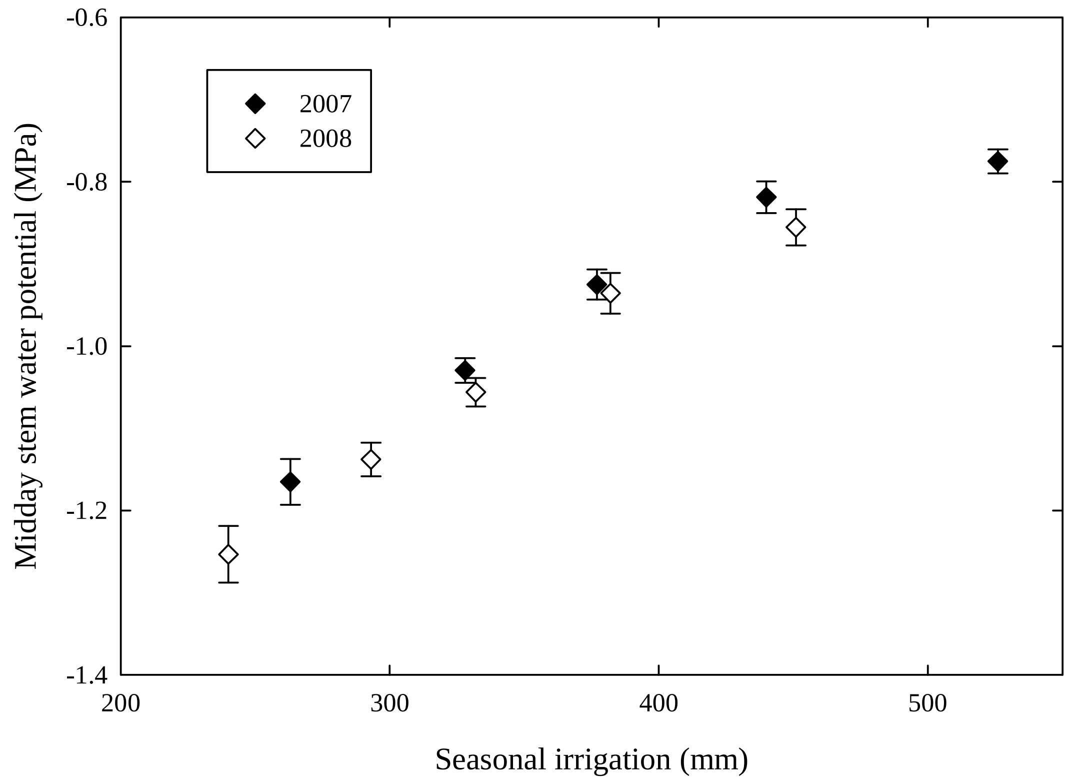

Fig. A.1 Preharvest midday stem water potential (Ψ_{stem}) of tart cherry trees under deficit irrigation from pit hardening to harvest was correlated with seasonal irrigation applied (mm).

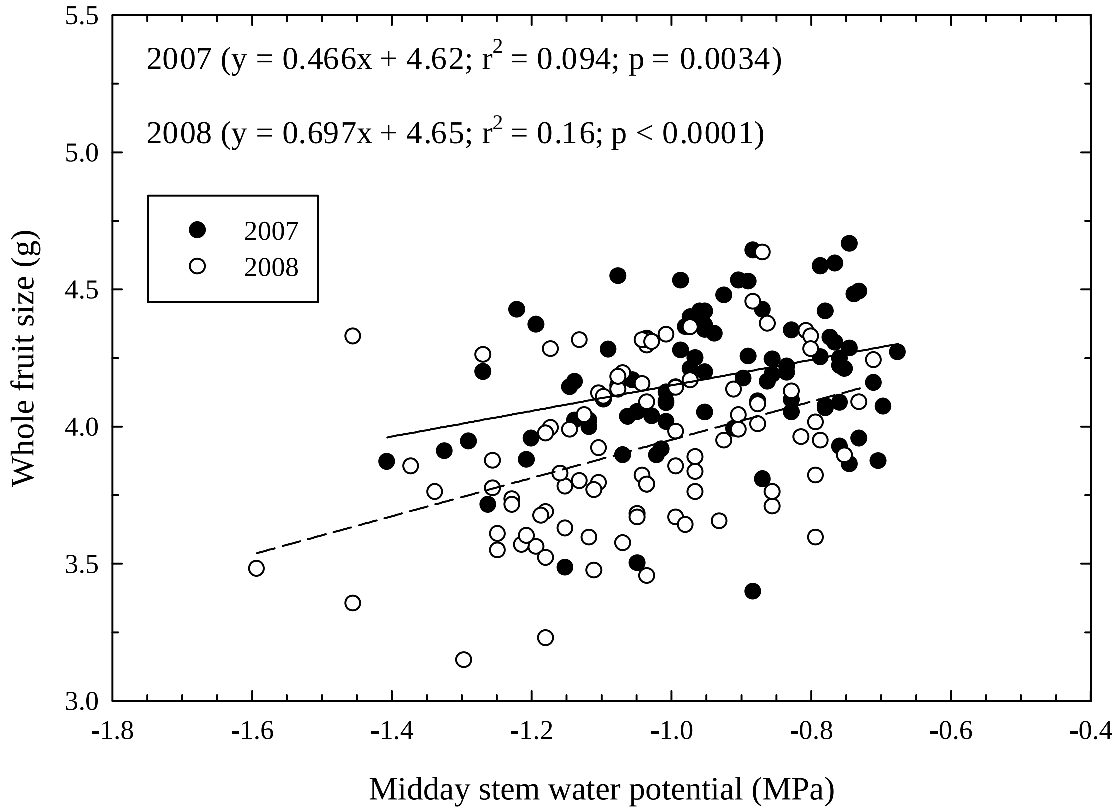

Fig. A.2 The relationship between fruit size (grams) and midday stem water potential (Ψ_{stem}) of tart cherry trees under deficit irrigation from pit hardening to harvest. Each value for whole fruit was the mean of a 15 fruit preharvest subsample.

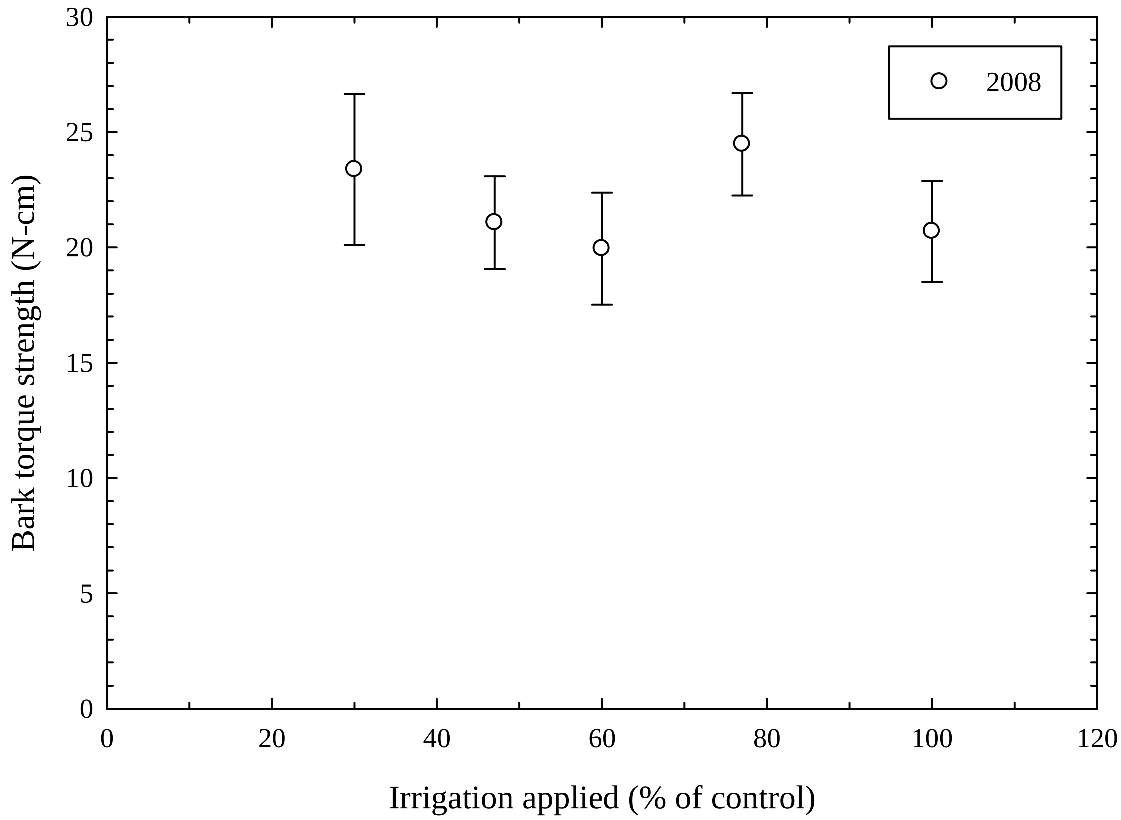

Fig. A.3 The effect of deficit irrigation from pit hardening to harvest on the torque force (N cm) required to remove a core of bark from the cambium of tart cherry trees. Each value is the average of two cores per tree, three trees per plot, and two replicate plots.