Interaction of Irrigation and Soil Management on Sweet Cherry Productivity and Fruit Quality at Different Crop Loads that Simulate Those Occurring by Environmental Extremes

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Abstract. ‘Cristalina’ and ‘Skeena’ sweet cherry cultivars (*Prunus avium* L.) on Gisela 6 (*Prunus cerasus* × *Prunus canescens*) rootstock planted in 2005 were maintained since 2006 in a randomly blocked split-split plot experimental design with six blocks of two irrigation frequency main plot treatments within which two cultivar subplots and three soil management sub-subplots were randomly applied. The focus of this study was the growth, yield, and fruit quality response of sweet cherry to water and soil management over three successive fruiting seasons, 2009–11, in a cold climate production area. The final 2 years of the study period were characterized by cool, wet springs resulting in low yield and yield efficiency across all treatments. Soil moisture content (0- to 20-cm depth) during the growing season was often higher in soils that received high-frequency irrigation (HFI) compared with low-frequency irrigation (LFI). HFI and LFI received the same amount of water, but water was applied four times daily in the HFI treatment but every other day in the LFI treatment. Consequently, larger trunk cross-sectional area (TCSA) and higher yield were found on HFI compared with LFI trees. Soil management strategies involving annual bloom time phosphorus (P) fertigation and wood waste mulching did not affect tree vigor and yield. Increased soluble solids concentration (SSC) occurred with LFI. Decreased SSC occurred with delayed harvest maturity in trees receiving P fertigation at bloom. The largest fruit size was correlated for both cultivars with low crop loads ranging from 100 to 200 g fruit/cm² TCSA. Overall cool, wet spring weather strongly affected annual yield and fruit quality, often overriding cultivar and soil and water management effects.

Research, primarily undertaken during the vegetative growth stage of sweet cherry (*Prunus avium* L.), has identified several management strategies to improve establishment of a new planting. These include pulse fertigation (Neilsen et al., 2010), surface mulching (Nuñez-Elisea et al., 2004), and polypropylene groundcover (Yin et al., 2007), which have improved nutrient and water acquisition. Little research has been conducted on water requirements for cherry (Hanson and Proebsting, 1996). It is not

surprising that there have been few studies on fruiting cherry trees with respect to novel irrigation strategies (Livellara et al., 2011) such as partial and deficit irrigation (Marsal et al., 2010), which have been intensively researched worldwide for several other tree fruits (Behboudian and Mills, 1997; Chalmers, 1989; Ebel et al., 2001; Naor, 2006).

There is increased recognition of the importance of the response of cropload on quality characteristics including fruit size (Marsal et al., 2010) and cracking (Measham et al., 2012). Low leaf-to-fruit ratios have been shown to increase fruit SSC, SSC/acid ratio, and delay maturity of ‘Lapins’ sweet cherry on Gisela 5 rootstock (Usenik et al., 2010). Another important source of annual quality variability is between- and within-year variation in environmental temperature, which is known to affect sweet cherry phenology, quality, and physiological disorders (Engin et al., 2009; Usenik and Stampar, 2011). In the important Canadian fruit-growing region of southern British Columbia, an analysis of long-term production records

(1920–91) indicated that two major factors limit production (yield) of sweet cherry. These are freeze injury from November to February (–13 to –24 °C nighttime temperatures) and low nighttime temperatures (–2 to –5 °C) around flowering (Caprio and Quamme, 2006). The latter factor is of particular interest because an important destabilizing effect on cherry production is extreme climatic events including frost injury as a consequence of early breaking of dormancy by sweet cherry (Neilsen et al., 2013).

This study was conducted to determine the response of two sweet cherry cultivars that were transiting from establishment to initial fruiting to various nutrient and water management strategies. The study was conducted in a cold climate and variable spring temperatures among years allowed evaluation of climate effects on growth, productivity, and fruit quality.

Materials and Methods

A sweet cherry orchard of ‘Cristalina’ and ‘Skeena’ cultivars on the dwarfing rootstock Gisela 6 (*Prunus cerasus* × *Prunus canescens*) was planted in Mar. 2005 at the Pacific Agri-Food Research Center (PARC) in Summerland, British Columbia, Canada. Since 2006 the experimental orchard has been maintained with the same treatments in a split-split plot with two main plot irrigation treatments, two cultivars as subplots, and three soil management treatments as sub-subplots with six replicates. Sub-subplots consisted of two measurement trees separated from adjacent subplots within the row by a shared guard tree at each end. Additional details of the establishment period (2005–08) can be found in an earlier publication (Neilsen et al., 2010). Pertinent to this discussion were the 2009–11 growing seasons when the orchard was in fruit production. The planting density was 2 m (between trees) × 4 m (between rows).

From 2006 to 2011, irrigation was scheduled with 100% evapotranspiration (ET) replacement of the previous day’s use based on evaporation from an electronic atmometer (ETgage Co., Loveland, CO) according to Parchomchuk et al. (1996) modified by crop coefficients. A crop coefficient curve, based on expected seasonal canopy development, was fitted to data from Allen et al. (1998). Each irrigation treatment received 100% ET replacement applied at HFI, 25% four times daily (0900, 1500, 2100, and 0300 HR), or LFI every second day at 0900 HR. Irrigation was applied through 4 × 4-L-h⁻¹ emitters located in two lines separated by 0.6 m either side of the tree row with emitters separated by 0.6 m in a square pattern centered on the tree.

Three soil management treatments were maintained throughout the experiment as 1) an unamended control; 2) a 10-cm wood waste mulch, which was maintained at this depth over a 2-m wide strip centered on the tree row; and 3) an annual fertigated application of 20 g P/tree at full bloom as ammonium polyphosphate (10N–15P–0K). Thus, the P fertigation treatment received

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annually an additional 13.3 g nitrogen (N)/tree in a single application applied with the P at bloom. For all treatments, a 2-m wide weed-free herbicide strip was maintained under the trees. The coarse-textured mulch ($\approx$ 1-cm diameter wood waste from British Columbia forestry operations) was selected based on its ready availability and potential to improve soil moisture by reducing evaporation from the soil surface. The two central sub-subplot trees were used for plant measurements leaving guard trees between each adjacent plot in each row. The six replicate treatment rows were bordered by a guard row, which surrounded the plot.

To ensure optimum plant nutrition, all treatments received annual fertigation applications of N, potassium (K), and boron (B), 2005–11. N was applied daily for $\approx$ 8 weeks post-bloom as calcium nitrate (15.5N–0P–0K) to supply 20 g N/tree/year. Potassium and B were applied daily for $\approx$ 4 weeks starting in early June. Potassium was applied as potassium chloride (0N–0P–50K) to supply 20 g K/tree/year. Boron was applied as Solubor (20% B) at 0.17 g B/tree/year. Standard commercial production practices controlled insects and diseases as required [British Columbia Ministry of Agriculture and Lands (BCMAL), 2010].

The soil at the experimental site was a Skaha loamy sand, an Aridic Haploxeroll, extensively planted to orchards in southern British Columbia (Wittneben, 1986). In a recent survey, two thirds of British Columbia cherry orchards were located on coarse-textured soils containing more than 50% sand-sized particles (sandy loam, loamy sands or sands) suggesting this site is representative of a majority of local orchards. Soils at the experimental site have limited water-holding capacity with volumetric moisture contents averaging 18% at field capacity (10 KPa) and 8% at the permanent wilting point (1500 KPa). Maximum and minimum daily temperatures from which average daily temperatures were calculated and daily precipitation were recorded at the nearby PARC weather station. The timing

of important phenological growth stages was recorded annually for each cultivar.

Trunk diameter at 0.3 m above the graft union was measured annually during dormancy (November to January) and used to calculate TCSA. Each year for each treatment and replicate, total annual crop was harvested and was weighed at the commercial harvest date for each cultivar. Yield efficiency (YE) was subsequently calculated by dividing harvest (kg) by the end of the growing season TCSA (cm^2) for each year.

A randomly harvested 100-fruit subsample was collected at each harvest to determine average fruit weight and the number of fruit splits for each treatment and replicate. Fruit firmness (FirmTech II; Bioworks, Stillwater, OK) and stem pull force (Dart FGV-5X digital force gauge; Shimpco America Corp, Ithasca, IL) were measured on a 20-fruit subsample. Color was also determined on the 20 fruit using the Michigan State University 1 to 5 scale chart (Michigan State University, East Lansing, MI). Juice extracted from this subsample was used to determine SSC with a digital refractometer (Model PR-101; AD Scientific Instruments, Keene, NM) and titratable acidity (TA) by autotitration to an 8.1 pH end point with data expressed as grams of malic acid equivalent per 100 mL of juice (Model 719S Titrino; Metrohm, Herisa, Switzerland).

Volumetric soil moisture content was measured using depth-integrated (0 to 20 cm) time domain reflectometry (Topp and Reynolds, 1998). Readings were made approximately weekly from May to September annually 2009–11 at 24 locations [for both ‘Skeena’ and ‘Cristalina’ cultivars $\times$ two irrigation treatments (HFI and LFI) $\times$ two soil management treatments (control and mulch) $\times$ three replicates]. The soil management treatment involving P fertigation was unmonitored because it was assumed its moisture content would be similar to the control treatment. Probes were located 0.3 m from the south side of measurement trees midway between the two emitters. Measurements were made just

before the 0900 HR irrigation on the LFI treatment.

Repeated-measures analysis of variance across years was performed on yield, TCSA, YE, and all fruit quality variables using a split-split plot experimental design with irrigation treatments as main plot units, replicated six times, cultivars as subplots, and soil management treatments as sub-subplots within each main plot. When there was a significant year $\times$ treatment interaction, treatment means were compared within years. Percent splits were arcsine square root-transformed before analyses. Soil moisture values were analyzed for each measurement day but with only two soil management sub-subplots and three replicates. Statistical analyses were undertaken using the mixed model procedure (SAS, 2006).

Results and Discussion

Climatic variation among years. Weather conditions throughout the 3-year experimental period indicated warm temperatures during the main sweet cherry growing months until harvest (April until July) in 2009 but that in both 2010 and 2011, average daily temperatures were below the 1971–2000 average in April and May (Table 1). In response to temperature, phenological development was affected with full bloom and harvest progressively later in the calendar year for each cultivar from 2009–11 (Table 2). Minimum daily temperatures during the critical April and May bloom development period indicated times when temperatures at the nearby but lower elevation Environment Canada weather station (Summerland CS 112G8L1) declined below freezing. Minimum temperatures of -1.1°C on JD 114 (24 Apr. 2009), which occurred at full bloom, -3.7°C on JD 110 (10 Apr. 2010) just before green tip, and a series of freezing temperatures JD 98, 102, 104 to 105, 109 to 110, and 112 to 113 in 2011 as the trees progressed from green tip to tight cluster from 8 Apr. through 22 to 23 Apr. reaching a minimum of -2.8°C at the Environment Canada weather

Table 1. Weather conditions during 2009–11 relative to long-term normals as measured at the Environment Canada Summerland–CS weather station.

Yr	Mean daily temp ($^\circ\text{C}$)											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
JD ^a	31	59	90	120	151	181	212	243	273	304	334	365
2009	-3.2	-1.2	2.4	8.2	14.3	19.3	23.3	21.5	17.5	8.0	4.5	-3.9
2010	1.2	3.3	6.5	3.4	12.3	17.0	21.9	20.8	15.1	10.8	0.9	-0.5
2011	-1.2	-1.5	4.8	6.9	12.4	16.5	19.5	21.8	18.1	3.3	2.2	-0.4
1971–2000	-2.5	0.2	4.7	9	13.6	17.4	20.5	20.2	15	8.8	2.4	-1.9
Monthly degree-day accumulation ($> 5^\circ\text{C}$)												
2009	0	0	16	103	288	427	567	512	373	104	16	0
2010	0	5	59	136	224	361	523	489	303	178	25	0
2011	0	2	34	58	228	345	449	520	392	135	4	1
1971–2000	2	5	32	123	266	371	479	471	229	128	19	2
Precipitation (mm)												
2009	nm ^b	nm	15	13	11	32	26	56	16	47	7	nm
2010	nm	nm	16	24	59	50	8	10	32	13	15	nm
2011	nm	nm	26	12	57	22	30	8	8	37	18	nm
1971–2000	30	21	19	26	36	36	30	30	20	18	28	33

^aNumber refers to last Julian day in each month. January starts at JD1.

^bNot measured (nm).

Table 2. Spring time phenological dates and harvest date for 'Cristalina' and 'Skeena' cultivars, 2009–11, and critical damaging thresholds for sweet cherry.

Yr	Cultivar	Phenological stage					Harvest date
		Side green	Green tip	Tight cluster	Full bloom		
2009	Cristalina	1 Apr. (1%) JD91	11 Apr. (70%) JD101	17 Apr. (75%) JD107	24 Apr. (60%) JD114		9 July JD190
	Skeena	1 Apr. (3%) JD91	11 Apr. (70%) JD101	17 Apr. (75%) JD107	24 Apr. (90%) JD114		22 July JD203
2010	Cristalina	5 Apr. (1%) JD95	14 Apr. (95%) JD104	21 Apr. (2%) JD110	6 May (100%) JD126		15 July JD196
	Skeena	5 Apr. (3%) JD95	14 Apr. (95%) JD104	21 Apr. (15%) JD110	6 May (100%) JD126		27 July JD208
2011	Cristalina	4 Apr. (80%) JD94	15 Apr. (100%) JD105	27 Apr. (10%) JD117	11 May (100%) JD131		21 July JD202
	Skeena	4 Apr. (50%) JD94	15 Apr. (20%) JD105	27 Apr. (90%) JD117	11 May (100%) JD131		2 Aug. JD214

Critical temperature thresholds ^a (°C)					
Sweet cherry					
10% kill	-5.6	-3.9	-3.3	-2.8	
90% kill	-12.8	-10.0	-8.3	-4.4	

^aData derived from Proebsting and Mills (1978).

station were recorded. This indicated the strong possibility of bud injury and yield reduction when compared with critical temperatures suggested for sweet cherry by Proebsting and Mills (1978). Furthermore, minimum temperatures lower than -19 °C on JD 343 and 344 (8 and 9 Dec.) 2008 were in the critical winter bud injury range suggested by Caprio and Quamme (2006) and were consistent with observations of blackened floral structures during spring bloom in 2009.

Soil moisture. There were no soil moisture differences among cultivars nor between mulched and unmulched treatments during the study period (data not shown). However, volumetric soil moisture content expressed as percent total available water (TAW) averaged over the 0- to 20-cm depth was usually significantly higher at HFI rather than LFI (Fig. 1). $TAW = (SM - PWP)/(FC - PWP) * 100$ where SM is percent volumetric soil moisture content, PWP is soil moisture content at the permanent wilting point (15 bars, 8% soil moisture), and FC is soil moisture content (0.1 bars, 18% soil moisture) (Ebel et al., 2001). Exceptions occurred in 2010 on JD 140 and 161 and in 2011 on JD 154 and 164

when LFI moisture contents were similar to HFI values after wet periods. Lack of a significant difference between HFI and LFI in 2011 after JD 216 reflected more variable soil moisture contents because the range between mean values was similar to values in 2009 and 2010 when averages were significantly different. In general, the overall results indicated that despite the occurrence of two successive cool, wet springs, decreased water availability was measured at LFI relative to HFI immediately before initiation of irrigation for LFI. This implied a higher probability for water stress to develop for the LFI trees over the 3 fruiting years of the study. This pattern was thus consistent with soil moisture difference between HFI and LFI trees during the establishment year of this experimental block (Neilsen et al., 2010). However, minimum soil moisture contents during the 2009–11 growing seasons often fluctuated between 50% to 75% TAW for LFI, above the 20% to 75% TAW range observed from 2006–08. However, Ebel et al. (2001) found for apple that significant water stress, reducing fruit growth rate, began at 30% to 35% TAW. This suggests

that during the 3 fruiting years, sweet cherry trees subjected to LFI could have been on the cusp of significant water stress.

Tree vigor and yield. Trunk cross-sectional area was affected by a three-way interaction of irrigation × cultivar × soil management ($P = 0.012^*$), but irrigation had the strongest influence on TCSA (Fig. 2). HFI trees were already larger at the start of fruit production as a result of irrigation treatment effects, which developed earlier during the vegetative period of the experiment in 2005–08. From 2009–11, when the same irrigation treatments were continued, relative differences in size between LFI and HFI trees became greater so that TCSA of LFI trees, which averaged 63.5% of HFI trees in 2009, was only 52.9% of HFI trees by 2011. However, the previous advantages for HFI trees of mulching and P application, which were apparent in 2009, had disappeared by 2011 as a consequence of greater increase in TCSA during 2009–11 of control trees receiving HFI, which continued canopy expansion so that tree canopies were closed within the rows by 2011.

Year-to-year variation in environmental conditions was manifested as significant year × irrigation, year × cultivar, and year × soil management interactions for yields and fruit quality measurements (Tables 3 to 5). Greater tree size (and hence canopy volume) was the likely reason for greater yield for HFI trees relative to those receiving LFI from 2009–11. Yield efficiency, in contrast, was greater for LFI in 2010 (Table 3). Soil management had no significant effect on yield or yield efficiency (data not shown). There were significant differences in cultivar performance during the study with 'Skeena' having higher yield and yield efficiency the first 2 years with the pattern reversed in 2011 (significant year × cultivar interaction). There were minor differences in spring phenological development of reproductive organs between the cultivars although in 2011, 'Skeena', despite its later harvest, reached tight cluster earlier than 'Cristalina' (Table 2). The poor yield performance of 'Skeena' in 2011 may reflect greater injury associated with the

Fig. 1. Average volumetric water content, 0- to 20-cm depth, for HFI (four times daily) and LFI (every second day) 100% ET replacement irrigation treatments, 2009–11 growing seasons. Expressed as percent total available water (TAW) where $TAW = (SM - PWP)/(FC - PWP) * 100$. SM = measured volumetric soil moisture content; PW = permanent wilting point, 8% water content; FC = field capacity, 18%; HFI = high-frequency irrigation; LFI = low-frequency irrigation; ET = evapotranspiration.

Fig. 2. Average trunk cross-sectional area as affected by irrigation and soil management treatments at the end of each growing season, 2009–11. Irrigation treatments include HFI (four times daily) or LFI (every second day) 100% ET replacement. Interaction SE was the same for all treatments (bars on the LFI mulch line represent ± 1 SE). HFI = high-frequency irrigation; LFI = low-frequency irrigation; ET = evapotranspiration.

Table 3. Effects of year $\times$ irrigation frequency and year $\times$ cultivar interactions on yield, yield efficiency, and fruit size for ‘Skeena’ and ‘Cristalina’ sweet cherry on Gisela 6 rootstock, 2009–11.

	Yield (kg/tree)			Yield efficiency (g·cm ⁻² TCSA)			Fruit size (g)		
	2009	2010	2011	2009	2010	2011	2009	2010	2011
Irrigation frequency (IF)^a									
HFI	12.1	10.2	11.8	236	196	169	9.8	10.3	11.8
LFI	7.7	7.7	6.5	231	233	166	9.6	9.6	11.5
Significance	***	*	***	NS	***	NS	NS	*	NS
Significance (Y $\times$ IF)		**			**			NS	
Cultivar (CV)									
Cristalina	4.4	6.8	11.9	120	186	229	10.9	9.8	10.2
Skeena	15.4	11.1	6.4	347	216	105	8.5	10.1	13.0
Significance	***	***	***	***	*	***	***	NS	***
Significance (Y $\times$ CV)		***			***			***	

^aIrrigated four times daily (HFI) or every 2 d (LFI) with the same quantity of water.

*, **, *** denote $P \leq 0.05$, $P \leq 0.01$, or $***P \leq 0.001$ or nonsignificantly different (NS).

TCSA = trunk cross-sectional area.

frequent April frosts immediately preceding tight cluster that year. Trees with large (i.e., HFI) but not small (LFI) TCSA had filled their in-row space by this time suggesting some but not all trees had constraints on canopy expansion. Also noteworthy during the study was a failure for overall tree yield to increase as TCSA increased during the study period. Thus, cropload steadily declined from 2009 so that values averaged below 200 g fruit/cm² TCSA by 2011. The occurrence of two successive cool, wet springs depressed yield. However, fruit size increased as cropload declined, being particularly large in 2011. There was a single year effect of irrigation on fruit size with larger fruit associated with HFI relative to LFI trees in 2010 when cropload of HFI trees was below 200 g fruit/cm² TCSA. Variation in annual fruit size between cultivars was associated with low cropload and with very large fruit for the specific cultivar.

The persistent negative consequences to tree size and yield for trees irrigated at low frequency during the establishment vegetative years through the first 3 years of fruit production illustrates the importance of maximizing tree size before initiation of fruiting. It could be speculated that once vigorous trees have been established, a mild stress

(such as drought) could promote the transition from vegetative to reproductive growth. Our data also demonstrates that HFI can continue to improve tree size when trees were fruiting. The diminishing effects of P application and mulching on yield and vigor implies that the benefits of these strategies, which were apparent in establishment years, are less important for fruiting trees under the observed relatively low yield levels. However, these treatments improved soil fertility and organic matter status and discontinuing them may create future limitations. In contrast, the influence of weather conditions on sweet cherry yield was indicated by the relatively low and declining cropload regardless of irrigation and soil management treatments. Caprio and Quamme (2006) previously reported that analysis of sweet cherry yield from 1920–91 in the Okanagan region indicated that the major climatic limitation to production was low nighttime temperatures (–13 to –24 °C) from November to February and that poor production was also associated with low nighttime temperatures (–2 to –5 °C) around flowering. Because both of these conditions occurred during the study period, this is the most likely reason for the observed low yield efficiencies. Furthermore, the reversal in 2011 of the patterns of greater yield,

yield efficiency, and large fruit size observed for ‘Skeena’ relative to ‘Cristalina’ in 2009–10 is an indication of the sensitivity of yield components to the interaction between phenological development and air temperature because ‘Skeena’ were more phenologically advanced that year.

Average fruit size increased from 9.7 to 11.6 g per fruit as average yield efficiencies declined from 234 to 168 g fruit per TCSA. It was not possible to attribute altered fruit size to soil or water management differences because large fruit size (exceeding 10 g) generally occurred when yield efficiency was less than 200 g fruit per TCSA in 2011 and for HFI fruit in 2010. Thus, although LFI was sufficiently stressful on this coarse-textured soil to result in less vigorous trees, yield efficiency had a greater influence on average fruit size. Little information is available concerning the interaction between water stress and crop intensity for sweet cherry. Marsal et al. (2010) found that postharvest water deficits influenced cropload in the next year and could lead to increased yield during an “off” year but with no reported effects on fruit size. However, research on other fruit crops has indicated a larger fruit size can be maintained despite deficit irrigation when cropload is low (Naschitz and Naor, 2005).

Fruit quality. Soluble solids concentration and color were the only fruit quality characteristics affected by year $\times$ irrigation and year $\times$ soil management interactions during the study (Table 4). Other measured quality parameters including juice TA, fruit firmness, stem pull force, and percent splits were affected by year $\times$ cultivar interactions only (Table 5). Fruit from LFI trees had higher SSC in 2 of the 3 years and P fertigation reduced SSC in 2010. Effects of irrigation on fruit color at harvest were inconsistent across years with fruit from LFI trees darker the first year only. In contrast to soil and water management, cultivar effects were usually significant each year. ‘Skeena’ had darker color than ‘Cristalina’ in all 3 years although the magnitude of these differences varied among years. ‘Skeena’ was usually harvested with lower stem pull force than ‘Cristalina’ with significant differences in 2010 and 2011. In general, ‘Skeena’ fruit had higher SSC, more acid (TA), and firmer fruit than ‘Cristalina’ with the exception of 2009 when ‘Skeena’ trees had the highest yield and yield efficiency measured in the study. There were significant differences in the percent splits between cultivars each year with ‘Skeena’ fruit being nearly split-free in 2009–10 but having highest split incidence (29.6%) in 2011. These differences in splitting occurred despite similar quantities of precipitation in July 2009 and 2011. Rainfall during the critical 3 weeks preceding commercial harvest totaled 11.6 mm in 2009 (six rainfall events, two exceeding 0.2 mm) and 16.2 mm in 2011 (nine events, five exceeding 0.2 mm).

During this period of relatively low croploads, the different soil and water management strategies had few consistent effects on fruit firmness, color, and soluble solids, which

Table 4. Effect of year $\times$ irrigation frequency and year $\times$ soil management interactions on fruit soluble solids and color at commercial harvest of 'Skeena' and 'Cristalina' sweet cherry on Gisela 6 rootstock, 2009–11.

	Soluble solids (%)			Color ^y		
	2009	2010	2011	2009	2010	2011
Irrigation frequency (IF) ^z						
HFI	20.2	19.9	18.5	4.7	4.5	4.9
LFI	21.4	20.8	18.7	4.8	4.5	4.9
Significance	***	**	NS	*	NS	NS
Significance (Y $\times$ IF)		*			*	
Soil management (SM)						
Control	20.7	20.6A	18.7	4.7	4.6A	4.9
Mulch	20.9	20.8A	18.8	4.7	4.6A	4.9
Phosphorus application	20.8	19.7A	18.3	4.7	4.3B	4.8
Significance	NS	**	NS	NS	***	NS
Significance (Y $\times$ SM)		NS			*	

^zIrrigation four times daily (HFI) or every 2 d (LFI) with the same quantity of water.

^yMichigan State color chart 1 to 5 scale.

*, **, *** denote significance at $*P \leq 0.05$, $**P \leq 0.01$, or $***P \leq 0.001$ or nonsignificant (NS).

Table 5. Effect of year $\times$ cultivar interaction on fruit quality characteristics of sweet cherry on Gisela 6 rootstock, at harvest 2009–11.

Cultivar (CV)	Color ^z			Soluble solids (%)			Titratable acidity ^y		
	2009	2010	2011	2009	2010	2011	2009	2010	2011
Cristalina	4.7	4.3	4.8	21.9	20.0	16.3	0.70	0.55	0.87
Skeena	4.8	4.7	5.0	19.7	20.7	21.0	0.72	0.84	1.29
Significance	*	***	***	***	*	***	NS	***	***
Significance (Y $\times$ CV)		**			***			***	
	Firmness (g·mm ⁻²)			Stem pull force (kg)			Splits (%)		
Cristalina	290	272	241	0.66	0.82	0.70	5.4	1.5	9.2
Skeena	267	334	280	0.42	0.65	0.62	0.5	0.1	29.6
Significance	***	***	***	***	**	NS	***	NS	***
Significance (Y $\times$ CV)		***			NS			***	

^zMichigan State color chart 1 to 5 scale.

^yUnits grams of malic acid equivalent/100 mL juice.

*, **, *** Means significantly different at $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$ or nonsignificantly different (NS).

are key quality parameters for sweet cherry (Kappel et al., 1996). Elevated SSC of LFI fruit where water stress was sufficient to reduce tree size was one of the most consistent quality effects. Deficit and reduced irrigation strategies applied to 'Braeburn' apple have similarly been associated with increased SSC (Behboudian et al., 1998) and increased fructose, sucrose, and sorbitol concentrations at harvest (Kilili et al., 1996). In contrast, P fertigation could be associated with reduced fruit SSC. Relatively few studies have assessed the response of sweet cherry to P fertigation, although Ystaas and Froynes (1995) also found cherry SSC to be negatively affected by P fertigation. In our study, the association of reduced SSC with reduced color suggested delayed maturity for P-fertigated fruit and hence a potential for later picking. The advantage of increased size as a consequence of delaying picking has previously been reported for gibberellic acid-treated fruit (Choi et al., 2002).

Cultivars are often selected based on desired differences in fruit quality characteristics including SSC and firmness (Kappel et al., 1998). It was therefore not unexpected that cultivar differences were a major influence on fruit quality variation in this study, particularly when comparisons were made between the early maturing Cristalina culti-

var, which lacks self-fertility, and the late-maturing, self-fertile 'Skeena'. 'Skeena' relative to 'Cristalina' was consistently harvested for darker fruit color and had reduced stem pull force, which is a further indication that reduced pedicel retention may be an issue for this cultivar (Wirth et al., 2009). Differences between cultivars could also vary by year, as illustrated by SSC, TA, and firmness, which were higher for 'Skeena' relative to 'Cristalina' except in 2009 when cropload was high. It is not possible to determine conclusively from our data if these year-to-year differences in fruit quality are primarily the result of variation in cropload or other factors acting independently on both, but the depressive effect of high fruit load on cherry SSC has been previously reported (Marsal et al., 2010). Einhorn et al. (2011) found in controlled thinning experiments over two growing seasons that average fruit size, SSC, firmness, and TA were increased on 'Sweetheart' sweet cherry on Mazzard rootstock on thinned trees with low cropload. Our results further suggest that high cropload can decrease fruit TA and firmness indicating that differences in fruit quality related to cultivars may be altered by differences in cropload. The large fluctuations in the incidence of splitting both between cultivars and from year to year likely reflects an interaction between

physiological stage of development and timing and intensity of precipitation (Sekse, 1995). However, Measham et al. (2009) did not find a link between extent of splitting and amount nor timing of preharvest precipitation.

Conclusions

Several soil management treatments, which improved establishment of sweet cherry on Gisela 6 rootstock, were continued for three fruiting seasons (2009–11), 2 years of which were characterized by cool and wet springs. HFI resulted in higher root zone soil moisture content relative to LFI despite reduced evaporative demand during part of the growing season. Differences in TCSA established by 2009 were associated with larger trees receiving HFI and persisted during fruiting in 2009–11, evidence of continued suboptimal performance of trees receiving LFI. The larger size of HFI trees resulted in higher yield during the study period but their yield efficiency did not exceed smaller trees receiving LFI. Yield was unaffected by mulching and P fertigation suggesting a reduced role for their effect during fruiting when augmented soil carbon and P reserves had been established. An important factor affecting yield during the study period was weather, which affected cultivars differently. Low yield and cropload in 2010 and 2011 were associated with cold, wet springs for 'Skeena' but not 'Cristalina'. Differences in cultivar response were related to their different rates of phenological development. Fruit size, an economically important yield component, was little affected by soil and water management but instead its variation was closely associated with variations in cropload. Low croploads during the study period may also have contributed to reduced effects of treatments on cherry quality characteristics other than size. Increased SSC was most affected with higher values occurring with stress associated with LFI and lower values occurring with delayed maturity associated with P fertigation. The mitigation of these effects at low cropload suggests that variation in cropload can make an important contribution to year-to-year variation in sweet cherry fruit quality and response to treatments.

Literature Cited

- Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. United Nations Food and Agriculture Organization, Rome, Italy.
- Behboudian, M.H., J. Dixon, and K. Pothamshetty. 1998. Plant and fruit responses of lysimeter-grown 'Braeburn' apple to deficit irrigation. J. Hort. Sci. Biotechnol. 73:781–785.
- Behboudian, M.H. and T.M. Mills. 1997. Deficit irrigation in deciduous orchards. Hort. Rev. 21:105–131.
- British Columbia Ministry of Agriculture and Lands (BCMAL). 2010. Integrated fruit production guide for commercial fruit growers. Interior district, Victoria, BC, Canada.
- Caprio, J.M. and H.A. Quamme. 2006. Influence of weather on apricot, peach and sweet cherry

- production in the Okanagan Valley of British Columbia. *Can. J. Plant Sci.* 86:259–267.
- Chalmers, D.J. 1989. A physiological examination of regulated deficit irrigation. *New Zealand J. Agr. Sci.* 23:44–48.
- Choi, C., P.A. Wiersma, P. Toivonen, and F. Kappel. 2002. Fruit growth, firmness and cell wall hydrolytic enzyme activity during development of sweet cherry fruit treated with gibberellic acid (GA₃). *J. Hort. Sci. Biotechnol.* 77:615–621.
- Ebel, R.C., E.L. Proebsting, and R.G. Evans. 2001. Apple tree and fruit responses to early termination of irrigation in a semi-arid environment. *HortScience* 36:1197–1201.
- Einhorn, T.C., D. Laraway, and J. Turner. 2011. Crop load management does not consistently improve crop value of ‘Sweetheart’/‘Mazzard’ sweet cherry trees. *HortTechnology* 21:546–553.
- Engin, H., F. Sen, G. Pamuk, and Z. Gokbayrak. 2009. Investigation of physiological disorders and fruit quality of sweet cherry. *Europ. J. Hort. Sci.* 74:118–123.
- Hanson, E.J. and E.L. Proebsting. 1996. Cherry nutrient requirements and water relations, p. 243–257. In: Webster, A.D. and N.E. Looney (eds.). *Cherries: Crop physiology, production and uses*. CAB Intl., Oxford, UK.
- Kappel, F., B. Fisher-Fleming, and E. Hogue. 1996. Fruit characteristics and sensory attributes of an ideal sweet cherry. *HortScience* 31:443–446.
- Kappel, F., W.D. Lane, R. MacDonald, K. Lapins, and H. Schmidt. 1998. ‘Santina’, ‘Sunpaca Celeste’ and ‘Sumnue Cristalina’ sweet cherries. *HortScience* 33:1087–1089.
- Kilili, A.W., M.H. Behboudian, and T.M. Mills. 1996. Composition and quality of ‘Braeburn’ apple under reduced irrigation. *Sci. Hort.* 67:1–11.
- Livellara, N., F. Saavedra, and E. Salgado. 2011. Plant based indicators for irrigation scheduling in young cherry trees. *Agr. Water Mgt.* 98:684–690.
- Marsal, J., G. Lopez, J. del Campo, M. Mata, A. Arbones, and J. Girona. 2010. Postharvest regulated deficit irrigation in ‘Summit’ sweet cherry: Fruit yield and quality in the following season. *Irrig. Sci.* 28:181–189.
- Measham, P.F., S.A. Bound, A.J. Gracie, and S.J. Wilson. 2009. Incidence and type of cracking in sweet cherry (*Prunus avium* L.) are affected by genotype and season. *Crop Pasture Sci.* 60:1002–1008.
- Measham, P.F., S.A. Bound, A.J. Gracie, and S.J. Wilson. 2012. Crop load manipulation and fruit cracking in sweet cherry (*Prunus avium* L.). *Adv. Hort. Sci.* 26:25–31.
- Naor, A. 2006. Irrigation scheduling and evaluation of tree water status in deciduous orchards. *Hort. Rev.* 21:105–131.
- Naschitz, S. and A. Naor. 2005. The effect of crop load on tree water consumption of ‘Golden Delicious’ apples in relation to fruit size: An operative model. *J. Amer. Soc. Hort. Sci.* 130:7–11.
- Neilsen, D., G. H. Neilsen, A. Cannon, B. Taylor, T. Van Der Gulik, S. Smith, and I. Losso. 2013. Assessing risks from climate change and variability in perennial horticultural crops. *Acta Hort.* 984:87–100.
- Neilsen, G.H., D. Neilsen, F. Kappel, P. Toivonen, and L. Herbert. 2010. Factors affecting establishment of sweet cherry on Gisela 6 rootstock. *HortScience* 45:939–945.
- Núñez-Elisea, R., M. Cahn, L. Caldiera, and C. Seavert. 2004. Effect of a synthetic row cover on soil moisture content, growth and fruiting of young sweet cherry trees (*Prunus avium* L. cv. ‘Regina’/Gisela 6). *HortScience* 39:850 (abstract).
- Parchomchuk, P., R.C. Berard, and T.W. Van der Gulik. 1996. Automated irrigation scheduling using an electronic atmometer, p. 1099–1104. In: Camp, C.R., E.J. Sadler, and R.E. Yoder (eds.). *Evapotranspiration and irrigation scheduling*. Amer. Soc. Agr. Engr. Proc. Intl. Conf., San Antonio, TX.
- Proebsting, E.L. and H.H. Mills. 1978. Low temperature resistance of developing flower buds of six deciduous fruit species. *J. Amer. Soc. Hort. Sci.* 103:192–198.
- SAS. 2006. SAS for mixed models. 2nd Ed. SAS Inst., Cary, NC.
- Sekse, L. 1995. Fruit cracking in sweet cherries (*Prunus avium* L.). Some physiological aspects—A mini review. *Sci. Hort.* 63:135–141.
- Topp, G.C. and W.D. Reynolds. 1998. Time domain reflectometry: A seminal technique for measuring mass and energy in soil. *Soil Tillage Res.* 47:125–132.
- Usenik, V., P. Orazem, and F. Stampar. 2010. Low leaf to fruit ratio delays fruit maturity of ‘Lapins’ sweet cherry on Gisela 5. *Sci. Hort.* 126:33–36.
- Usenik, V. and F. Stampar. 2011. The effect of environmental temperature on sweet cherry phenology. *Europ. J. Hort. Sci.* 76:1–5.
- Wirch, J., F. Kappel, and P. Scheewe. 2009. The effect of cultivars, rootstocks, fruit maturity and gibberellic acid on pedicel retention of sweet cherries (*Prunus avium* L.). *J. Amer. Pomol. Soc.* 63:108–114.
- Wittneben, U. 1986. Soils of the Okanagan and Similkameen Valleys. Ministry of the Environment Technical Report 10. British Columbia Soil Survey, Report 52, Victoria, BC, Canada.
- Yin, X., C.F. Seavert, J. Turner, R. Núñez-Elisea, and H. Cahn. 2007. Effects of polypropylene ground cover on soil nutrient availability, sweet cherry nutrition, and cash costs and returns. *HortScience* 42:147–151.
- Ystaas, J. and O. Froynes. 1995. The influence of Colt and F 12/1 rootstocks on sweet cherry nutrition as demonstrated by the leaf content of major nutrients. *Acta Agr. Sect. B. Soil and Plant Sci.* 45:292–296.