Age-related Changes in Response of Highbush Blueberry Plants to Drip Irrigation

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Abstract. A study was conducted in the Fraser Valley of British Columbia, Canada, to determine the effects of drip configuration (one or two lines with emitters spaced every 0.3 or 0.45 m) and irrigation at moderate or heavy rates (5 or 10 L/plant) in a mature planting of ‘Duke’ highbush blueberry (*Vaccinium corymbosum* L.). Results were compared with those published previously from the first 4 years after planting. Although plant size increased with irrigation rate when the plants were younger, there was no added benefit of heavy irrigation on growth in the older plants. However, the plants became more sensitive to soil water deficits with age and, therefore, unlike when they were younger, had greater yields when more water was applied. Berry size and fruit firmness were little affected by irrigation in the older plants, but antioxidants, measured as oxygen radical absorbance capacity (ORAC), were higher with than without irrigation, suggesting that irrigation has the potential to improve the health benefits of blueberries. Growth, yield, and fruit quality were unaffected by drip configuration in any year. Overall, the results revealed that the response of highbush blueberry to drip irrigation changed over time and indicated that irrigation management should be adjusted as a planting matures.

Drip irrigation has rapidly become the most popular method to irrigate blueberry in most countries, including the United States and Canada. Young plants often grow better with drip than with conventional sprinkler systems and, as a result, produce more fruit with much less water during the first year or 2 after planting (Bryla, 2008; Bryla et al., 2009, 2011). However, there is little information

currently available on the use of drip in mature plantings.

Canopy cover increases rapidly in blueberry and, therefore, results in much greater water use in older plantings. Holzapfel et al. (2004) found that the amount of water required for maximum production of blueberries nearly doubled between the second and seventh year after planting in Chile. The water use in the planting may also increase with cropload. Bryla and Strik (2007) found that water use in ‘Duke’ was as high as 70 mm/week in early June, before the beginning of harvest, but dropped quickly to 40 mm/week per week in late July, after harvest. Mingeau et al. (2001) found a similar decline in water use after harvest in ‘Bluecrop’ blueberry grown in containers. Thus, it is not unreasonable to expect that older plants with larger croploads will have greater water requirements.

The response of blueberry plants to the frequency of irrigation may also change as the planting matures. Blueberry is a shallow-rooted crop with most of its root system

confined typically to the top 0.5 m of soil. In a 5-year-old planting in Oregon, more than 90% of the fine roots were located at less than 0.3 m, and the highest density of roots were between 0.10 and 0.2 m (Bryla and Strik, 2007). Consequently, unlike many deeper-rooted plants, blueberry tends to use its available soil water quickly compared with most perennial crops and, therefore, requires frequent rain or irrigation to avoid water stress (Bryla, 2011).

In a recent study in the Fraser Valley of British Columbia, we found that plant growth and yield of ‘Duke’ blueberry were unaffected by irrigation rates of 5 L/plant and 10 L/plant applied several times per week compared with zero irrigation during the first 3 years after planting and was only greater with drip irrigation during the fourth year (Ehret et al., 2012). However, several fruit quality characteristics such as fruit size, firmness, and soluble solids concentration were affected a year or 2 earlier by irrigation, but neither yield nor fruit quality was affected by the configurations of the drip system in any year. The present study is a continuation of this previous work. The objective was to determine if the trends observed in the younger plants changed over time as the planting matured.

Materials and Methods

Study site. A 0.15-ha field of northern highbush blueberry (*Vaccinium corymbosum* L. ‘Duke’) was established at the Pacific Agri-Food Research Center, Agassiz, BC, Canada (lat. 49°14′33″ N, long. 121°45′35″ W) in Oct. 2006, as described previously (Ehret et al., 2012). Soil at the site was a moderately well-drained Monroe series (eluviated eutric Brunisol) silt loam. Data presented in the previous paper covered the 2008–10 growing seasons. This article presents data from the 2011 and 2012 growing seasons when the plants were in their fifth and sixth years of production, respectively.

Experimental design. Nine irrigation treatments were arranged in a randomized complete block design with six blocks and included all combinations of one or two lines of drip tape (DLT Heavywall Dripperline; Netafim, Fresno, CA), two drip emitter spacings, and two different volumes of irrigation (moderate and heavy) plus a non-irrigated control, which only received rainwater (Ehret et al., 2012). Depending on the year, either five or six plants were measured in each of the six replicates per treatment. Because no effects of line number or emitter spacing were statistically significant in this (data not presented) or the previous study (Ehret et al., 2012), data from line and emitter treatments were pooled within the irrigation volume treatments. Water was applied at rates of 5 and 10 L/plant per irrigation event in the moderate and heavy irrigation treatments, respectively, which was equivalent to 17,935 and 35,870 L·ha⁻¹ (7,260 and 14,520 L/acre).

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Irrigation was applied using a computerized Harrow Fertigation Manager (Climate Control Systems, Leamington, Ontario, Canada). As a guide, irrigation was initiated when average soil matric potential of the heavy irrigation treatment reached -20 to -25 kPa. However, as a result of system constraints in terms of water supply and weekend labor, irrigation could only be applied to a maximum of three to four times per week, resulting in the possibility of soil matric potentials gradually becoming lower even in the heavy irrigation treatment, depending on season. The treatments were irrigated sequentially over a 7-h period within a given day. Plants were irrigated 11 July to 9 Sept. in 2011 and 10 July to 28 Sept. in 2012. The total volume of water applied to the moderate and heavy irrigation treatments was 150 and 300 L/plant, respectively, in 2011, and 170 and 340 L/plant in 2012. The proportion of water applied before and during harvest was equivalent to 60% of the total in 2011 and 47% of the total in 2012.

Field management. Plants were fertilized (15–8–11; Berry Blend fertilizer; Terra Link Inc., Abbotsford, BC, Canada) in two equal broadcast applications in mid-April and mid-June of each year. Annual rates applied in 2011 and 2012 were 186 and 207 g/plant, respectively, using nitrogen rates recommended in the British Columbia Berry Production Guide (BCMAL, 2009). Soil pH was measured in samples collected with a standard $\frac{3}{4}$ -inch (1.9 cm) soil core sampler from the top 30 cm of the planting (after sawdust was removed) each fall in all treatments (one sample per treatment) and was always within the range of 4.5 to 5.2, which is recommended for blueberry (BCMAL, 2009). At the beginning of flowering each year, a honeybee (*Apis mellifera* L.) hive was positioned at the north end of the field to facilitate pollination. Bird netting was installed overall six blocks during berry ripening. Plants were pruned annually from January through March by the same person and according to industry standards (BCMAL, 2009). There were two pruning objectives; the first was to remove damaged, diseased, and crossed branches and any unproductive wood, which included small twiggy branches and old canes. The second objective was to shape the plant by removing any low branches that would touch the ground when loaded with fruit and by removing branches in the center of the plant to allow for light penetration and air circulation. Pests and disease were managed according to recommendations in the British Columbia Berry Production Guide (BCMAL, 2009).

Measurements. Rainfall and air temperature were recorded using environmental data loggers (HOBO U30 Weather Station; Onset, Bourne, MA) positioned 20 m from the plots. Daily potential evapotranspiration (ET_o) was measured with an atmometer (ETgage Model E; ETgage Company, Loveland, CO) fitted with Style #30 diffusion cover. The atmometer was placed within the plots at a height equivalent to the top of the plant canopy.

Soil matric potential (component of soil water potential resulting from adhesion of water molecules to soil particles) was measured hourly with granular matrix sensors (Watermark Model 900M Monitors; Irrrometer, Riverside, CA). All sensors were placed in treatment plots within the same three blocks. Each treatment plot had two sensors, one located halfway between two plants within the plant row and the other was located 19 cm from the plant row on either side of the bed. Thus, whether plots were irrigated using one or two lines of drip, one sensor was always located under a dripline (between two emitters) and the other was not. There was a total of six sensors per treatment but values for the two sensors in each plot were averaged ($n = 3$).

A time-domain reflectometry (TDR) system (E.S.I. Environmental Sensors, Sidney, BC, Canada) was used to measure soil water content at four 15-cm depth increments (0 to 15, 15 to 30, 30 to 45, 45 to 60 cm) in selected treatments. All probes were located in the same block with three probes in the control treatment (two in-row and one 35 cm from the plant row), two in the moderate irrigation treatment (one in-row and one 35 cm away), and three in the heavy irrigation treatment (two in-row and one 35 cm away). To achieve consistency with the limited number of probes, the moderate and heavy irrigation treatments were chosen to have a single line of drip tape with an 18-inch emitter spacing. All TDR probes were installed halfway between two emitters. Means for each day were calculated from 24 readings. Individual sensors were found to be somewhat variable in terms of output readings at a time when soil water content would have been the same in all treatments (in the spring before the start of irrigation), so values were normalized for each year as follows: a grand mean of daily values from segments of all sensors at the same interval was calculated for all days before the first irrigation. The mean for each individual sensor was then adjusted by subtracting the difference between it and the grand mean if higher than the latter and adding the difference if lower.

Fruit from each plot were hand-picked in two harvest periods each year. The amount of immature fruit in the second harvest in 2011 was estimated by determining the weight of immature fruit as a percentage of the total in one subsample per treatment replicate.

Fruit firmness was measured using a firmness meter (FirmTech 2 Fruit Firmness Tester; BioWorks, Wamego, KS). The Compression Force Threshold procedure with a fixed range of compression forces (selected by the operator) was used to measure the g force required to compress the fruit 1 mm. After load cell calibration and a reference size measurement, which is required for fruit diameter measurements, fruit were placed with the proximal end facing inward on a metal plate turntable. The instrument measured fruit firmness and diameter simultaneously at room temperature. Two runs of 50 fruit each were conducted per treatment in each block on every harvest date.

Titrateable acidity, soluble solids, and ORAC were measured using previously described methods (Ehret et al., 2012). Titrateable acidity and soluble solids were measured in 50 g of fruit per treatment plot and ORAC was measured in 50 berries from each treatment plot.

Plant size was estimated after fruit harvest of each year and was based on measurements of canopy height of all plants in each replicate. Canopy height was measured from the base of plants (at the surface of the sawdust) to the tip of an average length stem located at the top of the canopy. Flower buds were counted after the annual winter pruning on one (2011, 2012) or two (2013) average-sized plants (estimated visually) from each treatment in all replicates. Flower buds from prunings were also counted in 2011 and 2012.

Statistical analysis. All statistical analyses were carried out with the GLM or REG procedures of SAS (SAS Institute, Cary, NC). Irrigation line number and emitter spacing treatments had no effects on the plants so treatments were pooled by irrigation volume before analysis. The REG procedure was used to assess linear relationships between dependent and independent factors in the trials and used a model with dummy variables for those that were of a qualitative nature (year, block).

Results and Discussion

Yield increased with irrigation during both years of the study and was greater with heavy irrigation than with moderate irrigation in 2011 but not in 2012 (Table 1). Previously, we found that yield was unaffected by irrigation until the third year of fruit production (2010) and, in that case, only increased with moderate irrigation and only during the second harvest (Ehret et al., 2012). In other studies, Byers and Moore (1987) found no effect of irrigation in trickle-irrigated highbush blueberry grown in 140-L barrels of loam soil, but Haman et al. (1997) found an increase in yield in plants grown in lysimeters filled with sand. Previous studies have also shown reduced effectiveness of heavy compared with moderate irrigation rates on blueberry yield. Bryla et al. (2009) found no difference in highbush blueberry yield between plants treated with 100% and 150% of estimated crop evapotranspiration (ET). Holzapfel et al. (2004) found that

Table 1. Effects of irrigation level on fruit yield in 'Duke' blueberry in 2011 and 2012.

Irrigation level ^a	Yield by yr (t·ha ⁻¹)		Yield by harvest (t·ha ⁻¹) ^b	
	2011	2012	Harvest 1	Harvest 2
Non-irrigated	15.0 c ^x	17.2 b	11.9 b	4.2 b
Moderate	17.0 b	19.8 a	12.8 b	5.6 a
Heavy	19.5 a	20.2 a	13.9 a	6.0 a

^aModerate = 5 L/plant per irrigation; heavy = 10 L/plant per irrigation.

^bData were averaged over 2 years (2011–12).

^xMeans followed by the same letter within a column are not significantly different ($P > 0.05$), according to Duncan's multiple range test.

although highbush blueberry yield in drip treatments generally increased linearly with irrigation volume, plants treated with micro-jet irrigation showed a reduction in yield at the highest application volumes.

On average, over 2 years, yield was greater with heavy irrigation than with no irrigation during the first harvest and with either level of irrigation during the second harvest (Table 1). In earlier years, irrigation only affected yield of the second harvest (Ehret et al., 2012). Irrigation also reduced the proportion of immature fruit picked in the second harvest in 2011 (14.0%, 10.9%, and 10.5% in non-irrigated, moderate, and heavy irrigation, respectively; not evaluated in 2012) and, therefore, may have hastened fruit ripening. Thus, irrigation effects on yield were primarily the result of effects on later-ripening fruit when the plants were younger and as a result of effects on both early- and later-ripening fruit as the plants matured.

The treatment effects on fruit quality are summarized in Table 2. Berry weight was similar with or without irrigation in 2011 but was lower with moderate or heavy irrigation than with no irrigation in 2012. This observation was somewhat unexpected based on our results from earlier years, where both moderate and heavy irrigation increased berry weight in the younger plants (Ehret et al., 2012). Others have also shown that berries are larger in irrigated plants. Increasing irrigation from 50% to 100% of the crop's ET requirements increased berry size, although no further increases were observed at 150% ET (Bryla et al., 2009). Our results for 2012 are more in agreement with those of Mingeau et al. (2001), who examined the effects of water stress on blueberry harvest the next year and showed that a 20-d stress period during flower induction reduced flower buds and produced fewer but larger fruit the next season. Indeed, irrigation has been shown to increase the number of berries per bush (Haman et al., 1997; Holzapfel et al., 2004). Therefore, any effects of irrigation on fruit size in our study were likely the result of a complex interaction of flower bud number, percentage fruit set, leaf-to-fruit ratio, and water supply.

Fruit firmness was unaffected by irrigation in either year (Table 2). Again, this is in contrast to results from earlier years, in which heavy irrigation reduced fruit firmness, on average, over the first 3 years of production (Ehret et al., 2012). Antioxidant concentrations were higher with either level of irrigation than with no irrigation in 2011, but not in 2012 (Table 2) suggesting that irrigation at least has the potential to improve health benefits of blueberries. ORAC values ranged from 39 to 51 $\mu\text{mol TE/g}$ fresh weight, which are higher than those reported in a study of highbush blueberry cultivars (Ehlenfeldt and Prior, 2001) where ORAC values for 'Duke' were 16.1 $\mu\text{mol TE/g}$ fresh weight and values for 87 cultivars ranged from 4.6 $\mu\text{mol TE/g}$ to 31.1 $\mu\text{mol TE/g}$ fresh weight. There were no effects of irrigation on titratable acidity (grand means of 0.45% and 0.30% in 2011 and 2012, respectively). Finally, soluble solids

were greater with moderate irrigation than with heavy irrigation in 2011 but were similar between the irrigated (moderate and heavy) and the non-irrigated treatments in 2011 and among all three treatments in 2012 (Table 2).

Plant height with irrigation was greater with than without but was similar between the two irrigation levels (Table 3). Irrigation similarly resulted in taller plants when measured during the third and fourth years of the trial (2009–10). However, at that time, plant height also differed between the irrigation levels and was greater with heavy irrigation.

Flower buds were counted before irrigation was started each year and, therefore, would be influenced by irrigation applied the previous year. With that in mind, plants produced more flower buds with heavy irrigation than with no irrigation in 2011 and 2012, although the difference in 2012 was no

longer significant once the plants were pruned in 2012 (Table 3). Hence, the effects of irrigation on yield in 2012 were not related to the number of flower buds. By 2013, plants produced more flower buds with either moderate or heavy irrigation and the difference was significant after pruning (Table 3). The proportion of flower buds remaining after pruning was consistent among the treatments each year but varied somewhat between the 2 years (i.e., 55%, 56%, and 59% for non-irrigated, moderate, and heavy irrigation, respectively, in 2011 and 44%, 39% and 40% for the same treatments in 2012).

Although yield component analysis was not attempted, nor was it the intention of the study, it is likely that plant size, fruit size, and the numbers of flower buds all contributed to final yield in each treatment (Table 4). For example, in 2011, irrigated plants had greater

Table 2. Effects of irrigation level on fruit quality in 'Duke' blueberry in 2011 and 2012.

Irrigation level ^z	Berry wt (g) ^y		Fruit firmness (g·mm ⁻¹) ^x		Antioxidants ($\mu\text{mol}\cdot\text{g}^{-1}$) ^x		Soluble solids ("Brix")	
	2011	2012	2011	2012	2011	2012	2011	2012
Non-irrigated	2.07 a ^w	2.25 a	193 a	180 a	44 b	39 a	11.4 ab	11.4 a
Moderate	2.09 a	2.17 b	192 a	178 a	51 a	42 a	11.7 a	11.3 a
Heavy	2.04 a	2.16 b	191 a	180 a	51 a	43 a	11.3 b	11.4 a

^zModerate = 5 L/plant per irrigation; heavy = 10 L/plant per irrigation.

^yAverage of 100 berries in each treatment plot.

^xExpressed as total equivalent concentration per gram fresh weight of fruit.

^wMeans followed by the same letter within a column are not significantly different ($P > 0.05$), according to Duncan's multiple range test.

Table 3. Effects of irrigation level on plant height and flower bud number in 'Duke' blueberry in 2011–13.

Irrigation level ^z	Plant ht (cm)		Flower bud (no./plant)				
			2011		2012		2013
	2011	2012	Unpruned	Pruned	Unpruned	Pruned	Pruned
Non-irrigated	116 b ^y	151 b	636 b	352 b	1075 b	470 a	514 b
Moderate	127 a	166 a	707 ab	400 b	1134 ab	442 a	599 a
Heavy	131 a	171 a	786 a	464 a	1215 a	484 a	615 a

^zModerate = 5 L/plant per irrigation; heavy = 10 L/plant per irrigation.

^yMeans followed by the same letter within a column are not significantly different ($P > 0.05$), according to Duncan's multiple range test.

Table 4. Pairwise linear regression relationships among yield, plant height, flower bud number, berry weight, fruit firmness, and irrigation water volume in 'Duke' blueberry during the first 3 years of fruit production (2008–10) and the next 2 years (2011–12).

Years/factor	r^2 values ^z				
	Plant ht	Flower buds	Berry wt	Fruit firmness	Irrigation
2008–10 ^y					
Yield	0.94**	0.93	-0.90*	-0.28	-0.96
Plant ht		—	0.87	-0.43	—
Flower buds			0.86	-0.43	—
Berry wt				-0.31**	0.90***
Fruit firmness					-0.30*
2011–12					
Yield	0.32**	0.36***	-0.41	-0.56	0.41***
Plant ht		—	-0.42	-0.58*	—
Flower buds			-0.41	-0.56	—
Berry wt				0.56	-0.43*
Fruit firmness					-0.55
2008–12					
Yield	0.89***	0.90***	-0.86	-0.41	0.93***
Plant ht		—	0.84	-0.54	—
Flower buds			-0.84	-0.54	—
Berry wt				-0.42**	0.86
Fruit firmness					-0.42*

^zFor ease of reference, significant relationships are highlighted in bold.

^yData from Ehret et al. (2012).

* $P = 0.056$; **, *** $P < 0.05$, 0.01, and 0.001, respectively.

yield resulting from larger plant size and a greater number of flower buds; however, berry size was not a contributing factor that year. The next year, increased yield with irrigation was associated with larger plant size, exclusively; the number of flower buds was unaffected by irrigation and berry weight was actually lower. This suggests that the larger irrigated plants supported more but smaller fruit arising from an equivalent number of flowers, hence a greater fruit set in the irrigated plants.

TDR measurements confirm that increasing irrigation increased soil water content at each soil depth and that water content also increased with depth (Fig. 1). Furthermore, with the exception of the heavy irrigation treatment measured at the uppermost depth interval, water was, overall, more plentiful in 2011 than in 2012. Although irrigation was scheduled according to a general assessment of soil matric potential, differential additions combined with differential rates of ET between irrigation events resulted in treatment-related differences in matric potential that increased as the season progressed. Soil matric potentials measured from 2009 to 2012 were progressively more negative. In fact, soil matric potential for the heavy irrigation treatment in 2012 was the same as that of the non-irrigated treatment in 2009 (Fig. 2). This was probably attributable at least in part to increasing plant size (Table 3; Ehret et al., 2012) and therefore increased water uptake. Weather did not seem to be a factor. Comparing 2011 and 2012, for example, total rainfall during the period from first irrigation to last fruit pick was actually greater in 2012 than in 2011 (48.6 mm compared with 27.2 mm, respectively) and ET_o measured over the same period was similar in the 2 years (69.8 mm in 2012 compared with 75.7 mm in 2011). (Incidentally, although ET_o was greater than rainfall in both years, the non-irrigated plants were not visually water stressed, likely because of the relatively high water-holding capacity of the silt loam soil and the high soil water content at deeper depths as shown by the TDR data.) Over the same four growing seasons, the relationship between yield and matric potential shifted; in 2009 and 2010, change in yield per unit change in matric potential was small (slopes of 13.7 and -29.4, respectively), whereas in later years, a unit change in matric potential had a much larger effect on yield with slopes of -194 and -120 in 2011 and 2012, respectively (Fig. 2). Hence, as the plants matured, sensitivity to water deficit potentially increased.

After a total of 6 years of irrigation application (five with harvests), it was of interest to establish relationships among the measured parameters and to determine how plant response to irrigation may have changed over time (Table 4). In young plants (2008–10), overall yield was not directly affected by irrigation volume, which had been applied during that season. Rather, it was positively related to the cumulative changes in plant height (size) resulting from

Fig. 1. Average daily soil water content at a depth of 0 to 60 cm in field plots of 'Duke' blueberry depth with no irrigation or with moderate (5 L/plant per irrigation) and heavy (10 L/plant per plant) levels of irrigation. Measurements were collected over a 32-d period in 2011 and a 30-d period in 2012. SE bars were smaller than the symbols and ranged from ± 0.1 to 0.4.

Fig. 2. Relationships between soil matric potential and yield by year from 2009 to 2012. Each relationship consists of the means $\pm$ SE ($n = 3$) of yield and soil matric potential for non-irrigated, moderate, and heavy irrigation treatments in each year. Equations for linear regressions: 2009, $y = 13.7x + 4887$; 2010, $y = -29.4x + 17020$; 2011, $y = -194.1x + 24477$; and 2012, $y = -120.1x + 26382$.

irrigation applied during that season and all previous seasons. Like with younger plants, the yield of older plants (2011–12) was positively influenced by plant size, but additionally by irrigation volume and flower bud count. The relationship with flower buds is similar to observations made on native populations of highbush blueberry where yield was positively related to both flower buds per cane and flowers per bud (Pritts and Hancock, 1985). In terms of berry size, Maust et al. (1999) found that because increasing flower bud density reduces canopy establishment in

Southern highbush blueberry, berry size was reduced as flower buds increased. This may also be a partitioning issue in that plants that are source-limited (low carbohydrates) are unable to support larger berries when there is a large number of flowers. With a lower flower number, resources could be partitioned to developing fewer, larger berries. Whereas fruit size was not related to plant size, number of flower buds, or yield at any time in the study, it increased with irrigation volume in young plants but decreased in older plants. As suggested previously, this

reversal could have been the result of changes in the number of fruit supported by the plant although plant size increased as well.

Fruit firmness was unaffected by flower bud count or yield in either set of plants but was negatively related to irrigation volume and fruit size in young plants. However, the relationship between fruit firmness and size may be incidental as pointed out by Ehret et al. (2012). Fruit firmness in older plants, on the other hand, was only affected by plant size with larger plants having reduced firmness. Looking at broad relationships over the entire study (2008–12), yield was positively related to plant size, irrigation volume, and flower count, and fruit firmness was negatively related to irrigation volume and fruit size.

Conclusions

It is rare to find studies of blueberry that document annual effects of irrigation over an extended period. Over a 6-year treatment period (5 years with harvest), we have shown that plant response to irrigation changes over time and that some plant parameters are unaffected in a consistent manner. Plants become more sensitive to water deficit with

age as shown by a more pronounced relationship between yield and soil moisture. The factors that contribute to yield such as water supply, plant size, flower count, and berry size also change over time.

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