HORTSCIENCE 52(4):625–633. 2017. doi: 10.21273/HORTSCI11533-16

Potential of Deficit Irrigation, Irrigation Cutoffs, and Crop Thinning to Maintain Yield and Fruit Quality with Less Water in Northern Highbush Blueberry

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Additional index words. Vaccinium corymbosum, climate change, drought, fruit quality, water productivity, water use efficiency

***Abstract*. Drought and mandatory water restrictions are limiting the availability of irrigation water in many important blueberry growing regions, such as Oregon, Washington, and California. New strategies are needed to maintain yield and fruit quality with less water. To address the issue, three potential options for reducing water use, including deficit irrigation, irrigation cutoffs, and crop thinning, were evaluated for 2 years in a mature planting of northern highbush blueberry (*Vaccinium corymbosum* L. 'Elliott'). Treatments consisted of no thinning and 50% crop removal in combination with either full irrigation at 100% of estimated crop evapotranspiration (ET_c), deficit irrigation at 50% ET_c (applied for the entire growing season), or full irrigation with irrigation cutoff for 4–6 weeks during early (early- to late-green fruit) or late (fruit coloring to harvest) stages of fruit development. Stem water potential was similar with full and deficit irrigation but, regardless of crop thinning, declined by 0.5–0.6 MPa when irrigation was cutoff early and by >2.0 MPa when irrigation was cutoff late. In one or both years, the fruiting season was advanced with either deficit irrigation or late cutoff, whereas cutting off irrigation early delayed the season. Yield was unaffected by deficit irrigation in plants with a full crop load but was reduced by an average of 35% when irrigation was cutoff late each year. Cutting off irrigation early likewise reduced yield, but only in the 2nd year when the plants were not thinned; however, early cutoff also reduced fruit soluble solids and berry weight by 7% to 24% compared with full irrigation. Cutting off irrigation late produced the smallest and firmest fruit with the highest soluble solids and total acidity among the treatments, as well as the slowest rate of fruit loss in cold storage. Deficit irrigation had the least effect on fruit quality and, based on these results, appears to be the most viable option for maintaining yield with less water in northern highbush blueberry. Relative to full irrigation, the practice reduced water use by 2.5 $ML\cdot ha^{-1}$ per season.**

Most commercial blueberry (*Vaccinium* sp.) fields require a substantial amount of irrigation for profitable production. In the western United States, blueberry growers typically apply an average of 25–50 mm of water per week during the summer and up to 75 $mm\cdot week^{-1}$ during periods of peak water use (Bryla, 2011). However, many growers are facing serious water limitations due to warmer and drier weather conditions, increased regulations, and greater demand by other sectors (Dalton et al., 2013). For example, in 2015, blueberry growers in Oregon and Washington lost an estimated 14 million pounds of fruit due to heat and inadequate water for cooling and irrigation as a consequence of reduced water allotments from irrigation districts (Schreiber, 2016). This was more than a $20 million reduction in value to the industry. Growers in California are facing even more serious challenges due to an ongoing severe drought (Cooley et al., 2015). If water shortages continue to result in less water for irrigation, the total value of blueberry production and suitable farmland may be reduced substantially in the region.

Although it is difficult to predict how small fruit producers will attempt to mitigate for water shortages, long-term solutions might include drought-resistant cultivars and switching to more efficient irrigation systems and management methods. Many blueberry growers have already switched from using sprinklers to drip to increase irrigation efficiency, and are scheduling irrigation based on soil and weather conditions (Bryla, 2011). Additional strategies may include deficit irrigation or cutting off (stopping) irrigation at key developmental stages. Deficit irrigation is used successfully in many fruit crops, including peach [*Prunus persica* (L.) Batsch] and wine grape (*Vitis vinifera* L.), but it has not been well tested in berry crops (Chalmers et al., 1981; Fereres and Soriano, 2007; Goldhamer, 2007). The technique consists of restricting irrigation water applications during either a particular growth period or the entire growing season, without causing significant reductions in yield. Irrigation cutoffs may likewise be effective at reducing water use, provided the cutoffs occur during periods when water demands by the crop are low or less critical to fruit production. Preharvest irrigation cutoffs had no effect on yield in almond [*Prunus dulcis* (Mill.) D.A. Webb] and virtually eliminated hull rot at harvest (Goldhamer and Viveros, 2000). Previous work indicated that there may be analogous benefits to reducing preharvest irrigation in northern highbush blueberry (Bryla et al., 2009; Ehret et al., 2012, 2015). In this case, underirrigation by drip had no effect on yield in blueberry but increased fruit firmness and the content of sugar and acid in the berries, primarily as a result of a slightly smaller berry size.

Cropping thinning is also an effective strategy for dealing with soil water limitations in a number of fruit crops. For example, reducing crop loads during water deficits increased plant water status of peach (Lopez et al., 2006, 2010) and pear (*Pyrus communis* L.) (Marsal et al., 2008, 2010) and improved fruit quality of apple [*Malus* ×*sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.] (Mpelasoka et al., 2001; Neilsen et al., 2016). By thinning the crop when water is limited, competition for resources is reduced in the remaining fruit (Lopez et al., 2006; Proebsting and Middleton, 1980), resulting in larger fruit with better fruit quality and flavor (Crisosto et al., 1997; DeJong and Grossman, 1995; Wünsche and Ferguson, 2005). To avoid overthinning, thinning-intensity models have been developed according to the severity of water deficit for apple (Naschitz and Naor, 2005) and pear (Marsal et al., 2010). Similar models could easily be developed for blueberry, provided the strategy of reducing the crop load is cost-effective and actually

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Received for publication 27 Oct. 2016. Accepted for publication 26 Jan. 2017.

We gratefully acknowledge Amber Shireman and Ruth Hamlyn for technical assistance.

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mitigates reductions in production or quality under water-limited conditions. Thus, research is needed to determine whether there is any value to crop thinning during soil water deficits in blueberry.

The objective of the present study was to evaluate the potential of using deficit irrigation, irrigation cutoffs, and crop thinning to maintain yield and fruit quality with less water in northern highbush blueberry. Implementation of such strategies could result in immediate water savings and would enable growers and irrigation managers to optimize both on-farm and regional water use. Such information would be particularly critical in water-short years.

Materials and Methods

Site description. The study was carried out in a mature planting of 'Elliott' blueberry established in Apr. 2004 at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, OR (lat. 44°33′10″N, long. 123°13′9″ W, 68 m elevation). Elliott is a vigorous, late-season cultivar, commonly grown for commercial production in the United States, Canada, and Chile (Bañados, 2004; Strik and Yarborough, 2005). Soil at the site is a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerolls). The soil was adjusted to pH 5.5 by incorporating 670 kg·ha^{-1} of elemental S at 6 and at 10 months before planting. The plants were obtained from a commercial nursery as 18-month-old container stock (2.9 L) and were transplanted 0.8 m apart on raised planting beds. The beds were 0.4 m high × 0.9 m wide and centered 3.0 m apart. A 9-cm-deep layer of douglas fir (*Pseudotsuga menziesii* Franco) sawdust and 100 kg·ha^{-1} N from ammonium sulfate fertilizer were incorporated within the planting row (≈1.2 m wide) before shaping the beds. The beds were mulched with 5 cm of sawdust after planting and every other spring there afterward. A 1.1-m-wide alleyway of grass (a mix of *Lolium perenne* L. and *Festuca rubra* L.) was seeded between the rows and was maintained by mowing as needed. Weeds were controlled, as needed, by hand-weeding on the top of beds and by applying glyphosate herbicide at the base of beds. No insecticides or fungicides were applied to the field.

Experimental design. Treatments were arranged in a split-plot design with four irrigation regimes [full irrigation at 100% of estimated ET$_c$, deficit irrigation at 50% ET$_c$ (applied for the entire growing season), and full irrigation with irrigation cutoff for 4–6 weeks during early (early- to late-green fruit) or late (fruit coloring to harvest) stages of fruit development] as main plots and two crop thinning strategies (no thinning and 50% crop removal) as subplots. An additional main plot treatment with no thinning was overirrigated at 150% ET$_c$ to verify that irrigation at 100% ET$_c$ was sufficient to avoid plant water stress and soil water deficits during the growing season. Each main plot consisted of one row of eight plants and was replicated four times. Treatments were blocked to reduce the amount of irrigation pipe needed for the study and to adjust for slight differences in soil texture across the field. Only the middle six plants in each plot were used for measurements, and two of those were randomly selected before the 2011 and 2012 growing seasons for the no thinning and 50% crop removal treatments.

In the crop thinning treatment, ≈50% of the berries were removed from each cluster at 2–3 weeks after fruit set in late Apr. 2011 and by removing ≈50% of the flower buds from each lateral branch after normal pruning in Feb. 2012. The irrigation treatments were initiated in mid-May and continued until 20 Sept. in 2011 and 1 Oct. in 2012. Two laterals of drip tubing (UniRam 570; Netafim, Fresno, CA) were installed per row, with one line located at ≈0.2 m from each side of the plants. The tubing had 1.9 L·h^{-1} pressure-compensating, in-line emitters spaced every 0.45 m. Irrigation was scheduled weekly based on precipitation and daily estimates of ET$_c$ obtained from a nearby Pacific Northwest Cooperative Agricultural Weather Network AgriMet weather station (http://usbr.gov/pn/agrimet/) (Bryla, 2011). Each water application was controlled using an automatic timer and solenoids, and was measured using turbine water meters (Sensus Metering Systems, Uniontown, PA) installed at the inflow of each irrigation treatment. Soil water content was checked biweekly to a depth of 0.3 m (between two plants near the center of the bed) in each nonthinned treatment, using a time domain reflectometry system (model Trase I; Soilmoisture Equipment Corp., Santa Barbara, CA). The readings averaged 31% each year in plots irrigated at 100% and 150% ET$_c$, 22% in plots irrigated at 50% ET$_c$, and <11% within 2 weeks after irrigation was cutoff during early and late stages of fruit development.

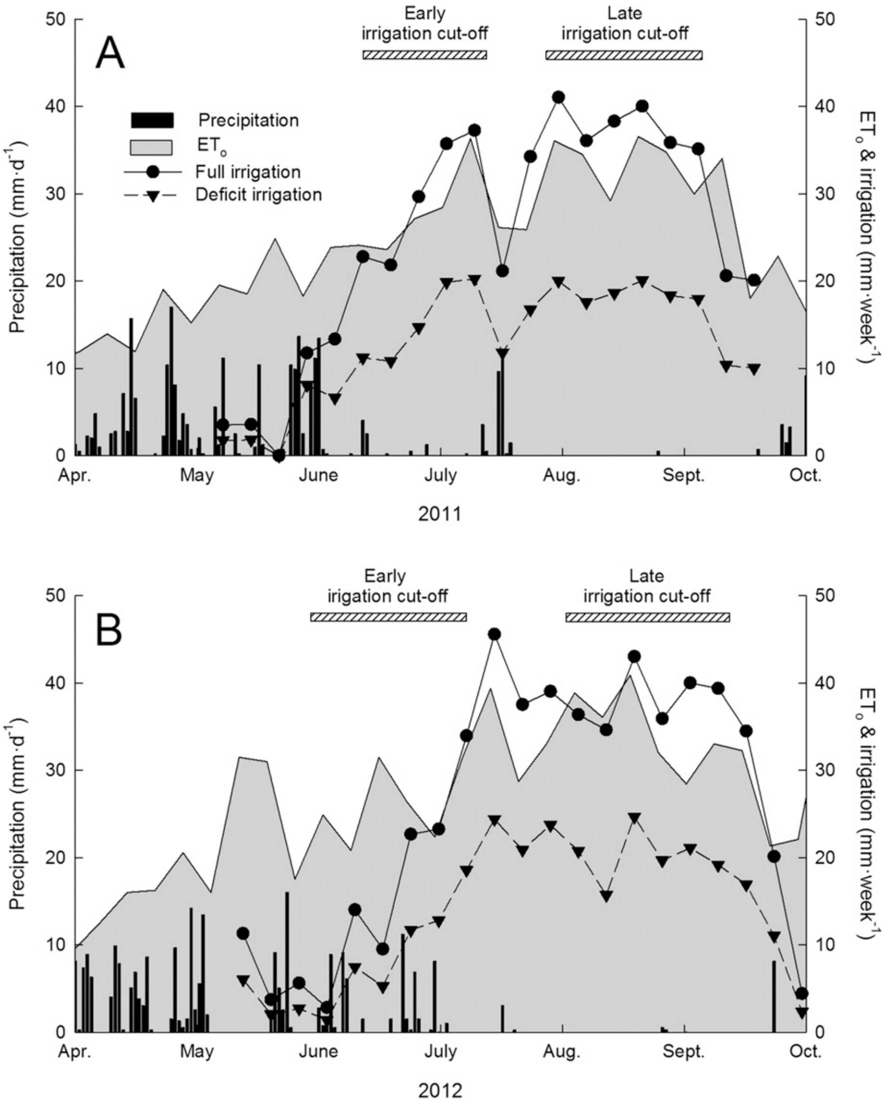

Fig. 1. Precipitation, potential evapotranspiration (ET$_o$), and irrigation applied to 'Elliott' blueberry grown in Oregon in (**A**) 2011 and (**B**) 2012. Four irrigation regimes were applied to the plants, including full irrigation at 100% of estimated crop evapotranspiration (ET$_c$), deficit irrigation at 50% ET$_c$, and full irrigation with irrigation cutoff during early (early- to late-green fruit) or late (fruit coloring to harvest) stages of fruit development.

Measurements. The plants were pruned during dormancy each winter, including on 3 Feb. 2012 and 8 Feb. 2013 during the present study. Any canes that were removed from the plants were gathered and weighed after pruning the plots. Only prunings from fully, deficit-, and over-irrigated plots (with no thinning) were weighed the first year, whereas all treatments were weighed the following year.

Fruit bud set was estimated after pruning by counting the total number of vegetative and flower buds on two randomly selected lateral branches (1-year-old wood) per plant. The laterals were chosen at midcanopy level and were ≈0.45 m long. Crop thinning was conducted after the fruit buds were counted in 2012.

The plants began flowering in mid to late April and set fruit in May. Berry development was measured from ≈75% fruit set and continued until the beginning of harvest each year. The third cluster from the distal end was tagged just before fruit set on one representative lateral per plant in each replicate. A random sample of five berries was marked in each cluster and measured for diameter every 3–5 d using a caliper in 2011 and digital images in 2012. The digital images were captured from a fixed position using a camera (Coolpix L105; Nikon Inc., Melville, NY) and analyzed using open-source ImageJ software (http://imagej.nih.gov/ij/). A metric ruler was placed next to the cluster in each image to serve as a scale for the diameter measurements.

Stem water potential was measured weekly from 9 June to 9 Sept. 2011 and 11 June to 28 Sept. 2012 using a pressure chamber (model 600; PMS Instrument Co., Albany, OR). The measurements were made at midday (1330–1530 HR) on mature, shaded leaves that were enclosed for at least 1 h inside dark plastic bags laminated with a reflective aluminum foil. A preliminary study indicated that water potential of bagged leaves (often referred to as stem water potential) was less variable within the plant than that of exposed leaves and, therefore, was a more sensitive indicator of water status of the plants (McCutchan and Shackel, 1992).

Ripe fruit were picked by hand and weighed in each plot on 16 Aug., 25 Aug., and 7 Sept. in 2011 and on 15 Aug., 29 Aug., and 13 Sept. in 2012. A random sample of 100 berries was also weighed from each plot on each date to determine the average weighted berry weight for the season. Another 25 berries were randomly sampled to determine average firmness and diameter using a firmness tester (model FirmTech 2; BioWorks Inc., Wamego, KS). Each berry was placed on its side on the instrument turntable, with the calyx facing inward. The compression force threshold procedure with a fixed range of compression forces (selected by the operator) was used to measure the firmness, which is reported as the mean gram force (N) of compression per millimeter.

About 150 g of berries were frozen from each replicate on each harvest date in 2012 and later analyzed for soluble solids (°Brix), pH, and titratable acidity. The frozen samples were thawed and pureed in a blender and measured for soluble solids using a refractometer (model PAL-1; Atago U.S.A. Inc., Bellevue, WA) and for pH using a dual pH-ion meter (model S80 SevenMulti; Mettler Toledo, Columbus, OH). A 10-g sample of the puree was mixed with 100 mL of distilled water and titrated with $0.1\ \mathrm{mol \cdot L^{-1}}$ NaOH to an endpoint pH of 8.1. Titratable acidity was calculated as a percentage of citric acid.

A final sample of berries (125 ± 1 g) from each replicate was placed into 0.24-L perforated plastic (polyethylene terephthalate) clamshells (Pactiv, Lake Forest, IL) on each harvest date in 2012 and stored in a walk-in cooler for 7–8 weeks. The cooler was set at 4 ± 1 °C. Relative humidity inside the cooler ranged from 95% to 99%. The berries were dry before placing them into the clamshells and had no visible signs of damage. The clamshells were inspected weekly for soft and wrinkled fruit, decay, and fungal infection. Once symptoms occurred, healthy and compromised berries were weighed separately to determine the percent fruit loss.

Statistical analysis. Student's t tests were used to determine whether there were any significant differences between the treatments irrigated at 100% and 150% ET_c. Each measurement, including stem water potential, pruning weight, fruit bud set, yield, berry weight and diameter, firmness, soluble solids, titratable acidity, or percent fruit loss, was similar between the two treatments, suggesting that irrigation at 100% ET_c was sufficient to avoid plant water stress in the study. Therefore, the data from plants irrigated at

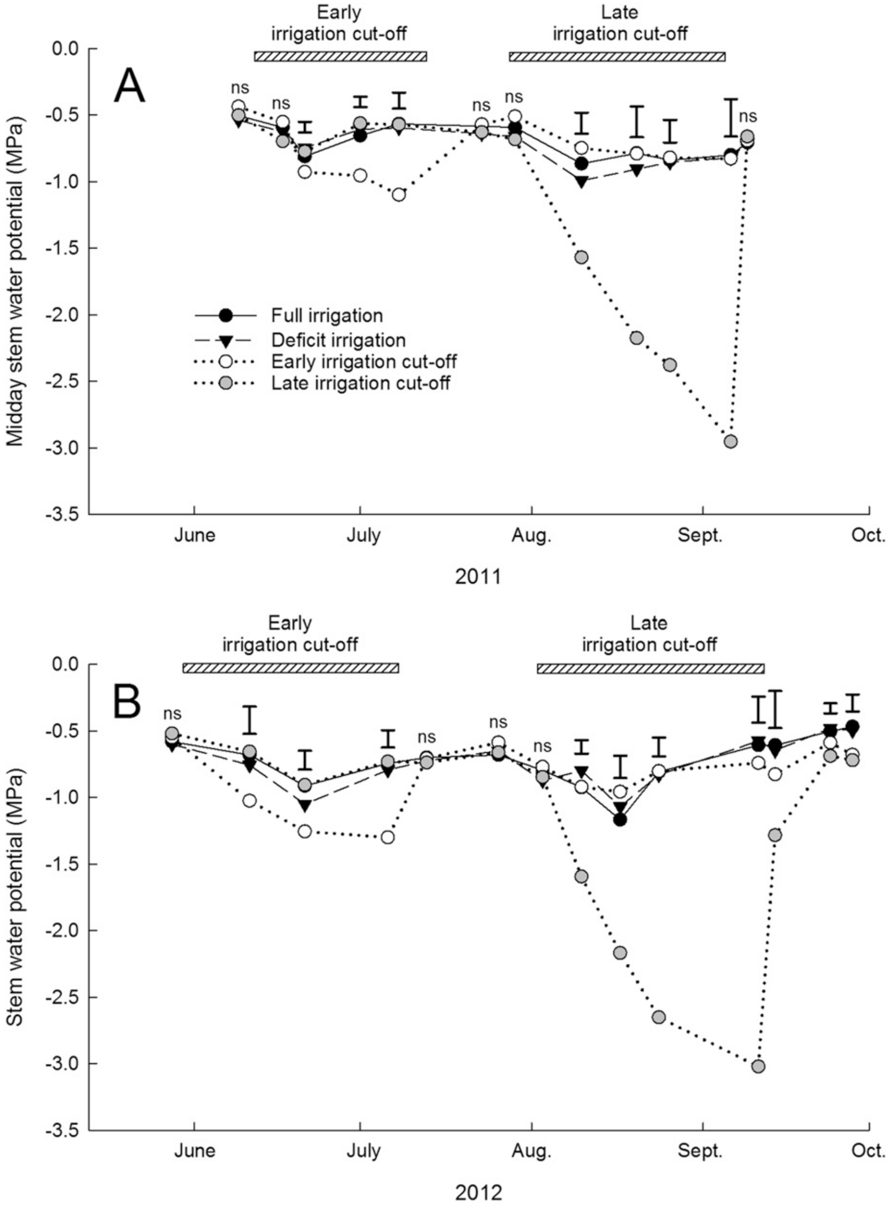

Fig. 2. Independent effect of four irrigation regimes on midday stem water potential of 'Elliott' blueberry grown in Oregon in (**A**) 2011 and (**B**) 2012. The values represent the average of plants with no crop thinning. Verticals bars on a given date indicate the least significant difference at $P \leq 0.05$. ns, nonsignificant.

150% ET_c were not included in any of the additional analyses.

The remaining data were analyzed by analysis of variance using SAS v. 13.2 (SAS Institute, Cary, NC). Repeated measurements, such as berry diameter, stem water potential, and percent fruit loss, were first analyzed over time, with each time of observation treated as a sub-subplot. Fruit loss during storage was the only measurement affected by a three-way interaction (irrigation and crop thinning treatments and date of observation), and the interaction was significant on each of the three fruit harvest dates ($P \leq 0.05$). Harvest date was also included as a sub-subplot for several measurements, including berry diameter at harvest, the proportion of yield removed on each harvest date, and fruit firmness, soluble solids, and titratable acidity. In each case, there were significant three-way interactions among irrigation, crop thinning, and harvest date ($P \leq 0.05$). Therefore, the results are presented for each harvest date.

Table 1. Independent effects of four irrigation regimes and two crop thinning strategies on fresh winter pruning weights and fruit bud set of 'Elliott' blueberry grown in Oregon.

	Pruning wt (kg/plant)		Fruit bud set (%)[z]	
Treatment	2011	2012	2011	2012
Irrigation				
Full irrigation	0.74 a[y]	0.74 a	39 b	42 b
Deficit irrigation	0.59 b	0.60 b	41 b	40 b
Early irrigation cutoff	n.d.	0.77 a	48 a	50 a
Late irrigation cutoff	n.d.	0.84 a	29 c	31 c
Crop thinning				
None	—	0.74	48	40
50% crop removal	—	0.73	31	41
Significance				
Irrigation	*	*	**	**
Crop thinning	—	NS	**	NS
Irrigation × thinning	—	NS	NS	NS

n.d. = not determined.

[z] Number of fruit buds divided by the total number of buds on a fruiting lateral.

[y] Means followed by the same letter are not significantly different ($P \leq 0.05$) within a year.

NS, *, ** Nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively.

Planned comparisons between full irrigation and other irrigation regimes were performed at the 0.05 level using Fisher's protected least significant difference test, whereas combined effects of irrigation and crop thinning were separated using Tukey's honest significant difference test ($P \leq 0.05$).

Results and Discussion

Weather and irrigation. Weather conditions were mild and dry throughout much of the growing season in 2011 and 2012, which is typical for the region (Fig. 1). Daily temperatures averaged 6–27 °C in April through September and were never <–1 °C or >38 °C in either year. Rain occurred primarily from April to June during the growing season and totaled 251 mm in 2011

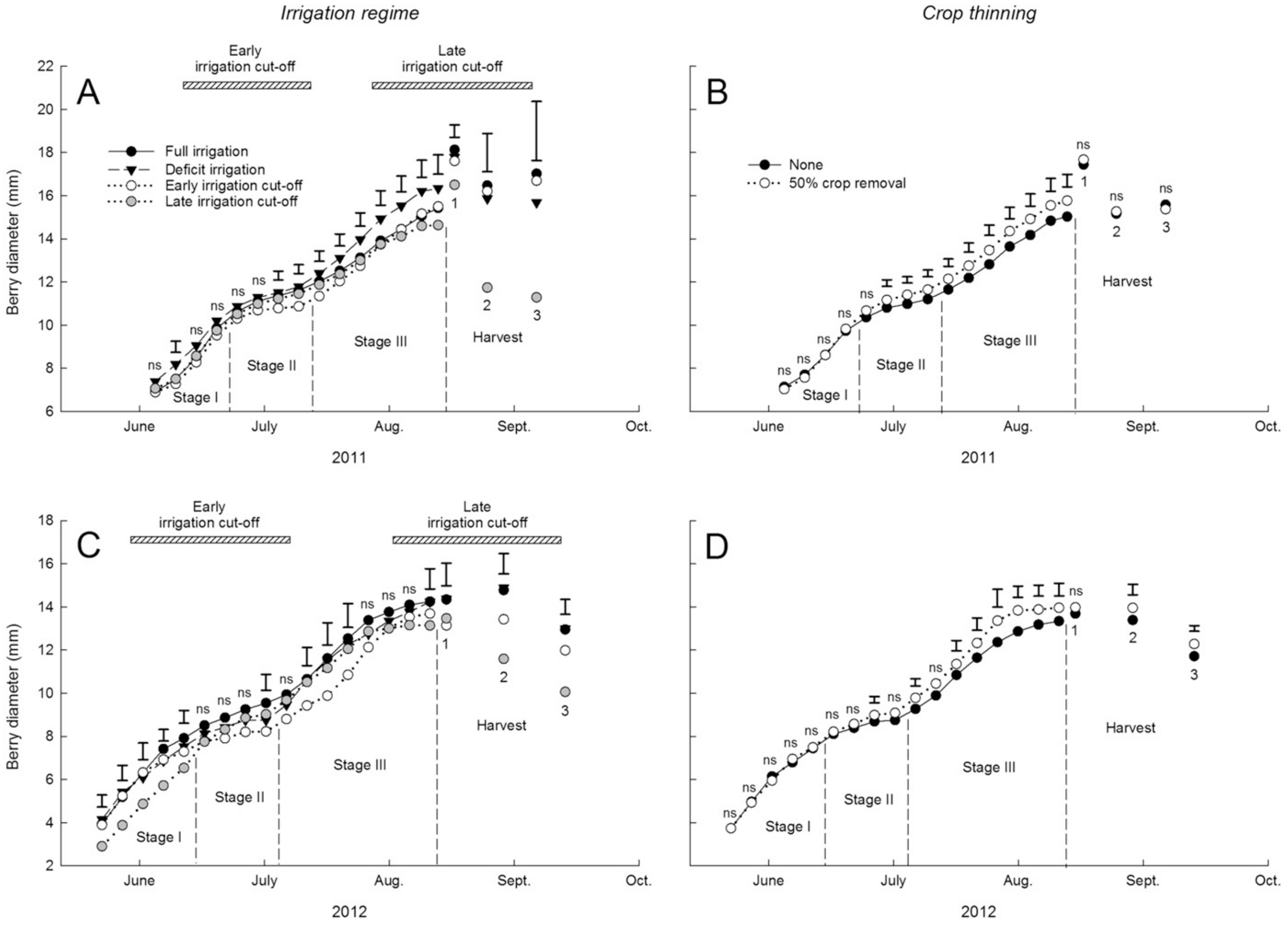

Fig. 3. Independent effects of (**A**, **C**) four irrigation regimes and (**B**, **D**) two crop thinning strategies on berry development of 'Elliott' blueberry grown in Oregon in (**A**, **B**) 2011 and (**C**, **D**) 2012. Diameter was measured nondestructively before harvest on the same berries over time (Stages I–III) and on random samples of picked berries on each harvest date (Harvests 1–3). Verticals bars on a given date indicate the least significant difference at $P \leq 0.05$. ns, nonsignificant.

Table 2. Independent and combined effects of four irrigation regimes and two crop thinning strategies on the proportion of total yield removed on each harvest date of ‘Elliott’ blueberry grown in Oregon.

	Yield (%)							
	2011			2012				
Treatment	Harvest 1	Harvest 2	Harvest 3	Harvest 1		Harvest 2		Harvest 3
Irrigation				No thinning	50% crop removal	No thinning	50% crop removal	
Full irrigation	48 b[z]	37 a	16 a	44 b	63 a	32 bc	29 bc	16 b
Deficit irrigation	76 a	18 b	6 b	48 b	65 a	37 ab	27 c	11 b
Early irrigation cutoff	40 b	40 a	20 a	19 c	29 c	42 a	42 a	34 a
Late irrigation cutoff	73 a	25 b	2 b	69 a	69 a	28 bc	30 bc	2 c
Crop thinning								
None	50	33	17	45		35		20
50% crop removal	62	31	7	56		32		11
Significance								
Irrigation	**	**	**	**		**		**
Crop thinning	**	NS	**	**		NS		**
Irrigation × thinning	NS	NS	NS	*		*		NS

[z] Means followed by the same letter are not significantly different ($P \leq 0.05$) within a harvest date.

NS, *, **Nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively.

Table 3. Independent and combined effects of four irrigation regimes and two crop thinning strategies on yield and berry weight of ‘Elliott’ blueberry grown in Oregon.

	Yield (kg/plant)			Berry wt (g)	
Treatment	2011	2012		2011	2012
Irrigation		No thinning	50% crop removal		
Full irrigation	3.6 a[z]	6.3 a	5.7 ab	1.92 a	1.74 a
Deficit irrigation	3.0 ab	5.3 abc	4.5 cd	1.89 ab	1.68 a
Early irrigation cutoff	4.0 a	5.1 bc	6.4 a	1.78 b	1.33 b
Late irrigation cutoff	2.7 b	3.8 de	2.9 e	1.38 c	1.39 b
Crop thinning					
None	4.3	5.1		1.71	1.44
50% crop removal	2.6	4.9		1.83	1.63
Significance					
Irrigation	*	**		**	**
Crop thinning	**	NS		*	**
Irrigation × thinning	NS	*		NS	NS

[z] Means followed by the same letter are not significantly different ($P \leq 0.05$) within a year.

NS, *, **Nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively.

and 244 mm in 2012. Potential ET, in contrast, was greatest in July to September each growing season and totaled 653 and 710 mm, respectively.

Full irrigation required a total of 502 mm (1170 L/plant) of water in 2011 and 537 mm (1250 L/plant) in 2012 (Fig. 1). Based on the water meter readings, 49% and 46% less water was applied each year, respectively, with deficit irrigation. The early irrigation cutoff treatment was carried out between late May and early July during the early- to late-green stage of fruit development, and the late cutoff treatment was applied between late July and early September during fruit coloring and harvest. The cutoff treatments were fully irrigated at 100% $\mathrm{ET_c}$ during the rest of the year. Rainfall totaled 13 and 64 mm each year, respectively, during the early cutoff period and <1 mm during the late cutoff (Fig. 1). Relative to full irrigation, the early cutoff saved an average of 1.3 $\mathrm{ML \cdot ha^{-1}}$ of water per year, whereas the late cutoff saved 2.3 $\mathrm{ML \cdot ha^{-1}}$ per year. Deficit irrigation saved ≈2.5 $\mathrm{ML \cdot ha^{-1}}$ of water per year.

Plant water status. Stem water potential was largely unaffected by deficit irrigation each year, but dropped to –1.2 to –1.3 MPa during the early irrigation cutoff treatment and to as low as –3.0 to –3.2 MPa during the late cutoff (Fig. 2). Water potential declined less severely during the early cutoff due to occasional rain and lower plant water demands at that time of year (Fig. 1). Previously, Bryla and Strik (2007) examined weekly water deficits in three cultivars of northern highbush blueberry, including an early-season cultivar, Duke, a midseason cultivar, Bluecrop, and Elliott, and found that, regardless of the weather conditions, water potential declined most readily just before harvest in each of the cultivars. This was attributed to higher $\mathrm{ET_c}$ during fruit ripening. Mingeau et al. (2001) reported that over half of the total seasonal water requirements of ‘Bluecrop’ occurred during the final stages of fruit development. Overall, there were no visible symptoms of water stress during the early irrigation cutoff treatment in the present study. The late cutoff treatment, on the other hand, resulted in leaf wilting within 2 weeks of treatment and in marginal leaf necrosis by the 4th week. In either case, water potential increased rapidly once irrigation was resumed. Améglio et al. (2000) determined that ‘Bluecrop’ required 7–9 d to completely recover from an episode of drought.

Stem water potential was only slightly affected by crop thinning each year ($P \leq 0.05$). On average, the values were 0.1 MPa lower in plants with no thinning than in those with 50% of the crop removed (data not shown). Marsal et al. (2010) likewise found that crop thinning had a minimal effect on midday stem water potential of pear trees irrigated at either 50% or 100% $\mathrm{ET_c}$. However, when the pear trees were irrigated at 20% $\mathrm{ET_c}$, water potentials were up to 0.4 MPa higher with 50% crop removal than with no thinning, and up to 0.6 MPa higher with 75% crop removal. It is possible that crop thinning would have a similar effect at lower levels of deficit irrigation in blueberry, provided that fruit growth was not limited by water stress under such conditions.

Fresh pruning weight and fruit bud set. Deficit irrigation generally produced less pruning weight than full irrigation each year and the lowest pruning weights among the treatments the 2nd year (Table 1). Deficit irrigation generally reduces vegetative growth in many crops, including northern highbush blueberry (Bryla et al., 2011). Irrigation cutoffs, on the other hand, had no effect on pruning weight relative to full irrigation, but in this case, the treatments were only measured the 2nd year. Crop thinning also had no effect on pruning weight the 2nd year.

Fruit bud set varied among the treatments each year and was generally greater in plants with early-irrigation cutoff than in those with full or deficit irrigation, and was lowest in plants with late-irrigation cutoff (Table 1). Bud set was also lower among treatments with crop thinning than those without crop thinning the first year but not in the 2nd year. More shoot growth was observed after 50% of the berries were removed the first year, but less so when the crop was thinned by pruning the 2nd year (K.F. Almutairi, personal observations). In many crops, fruit removal results in greater vegetative growth, which in the case of blueberry, will reduce fruit bud set (Ehlenfeldt, 1998; Jorquera-Fontena et al., 2014).

Berry development and ripening. Berry development was significantly affected over time by the irrigation regimes ($P \leq 0.01$) and crop thinning ($P \leq 0.01$) each year (Fig. 3). In each case, berry development followed a typical double-sigmoid pattern, with an initial period of rapid growth (Stage I) from late May to mid or late June, a lag period of slow growth (Stage II), and finally a second period of rapid growth followed by fruit ripening (Stage III) from early or mid-July to early September. This growth pattern is common in many fruit crops, including other *Vaccinium* species (Eck, 1988), and is attributed to rapid cell division of the endosperm in Stage I, seed development in Stage II, and rapid enlargement of the endosperm cells in Stage III (Bailey, 1947; Bell, 1957; Eck, 1986). Stages I and III are usually considered the most sensitive periods to water deficits (Bryla, 2011). Irrigation cutoffs were applied to incur water stress primarily during the slowest periods of berry growth, including Stage II (early) and the final stages of ripening (10% to 100% blue) in Stage III and harvest (late). Based on previous results, we expected that withholding irrigation would have a minimal effect on fruit production when the water was restricted during early stages of berry development and may improve fruit flavor and firmness at later stages of development (Bryla et al., 2009; Ehret et al., 2012, 2015).

In 2011, deficit irrigation increased the rate of berry development relative to full irrigation (Fig. 3A). Consequently, a greater proportion of the fruit ripened earlier and was picked sooner with deficit irrigation than with full irrigation that year (Table 2). Deficit irrigation had no effect; however, on berry development or the timing of the fruiting season the following year. Early irrigation cutoff, in contrast, reduced the rate of berry development and delayed fruit ripening in the 2nd year (Fig. 3C; Table 2), whereas cutting off irrigation in the late season delayed early fruit development during the spring following the treatment in 2012 (Fig. 3C) and accelerated the harvest season in both years (Table 2). The onset of fruit ripening is often hastened by water deficits due to a stress-induced increase in endogenous ethylene (Barry and Giovannoni, 2007). Crop thinning also increased the rate of fruit ripening (Table 2), as well as berry development, beginning at Stage II each year (Fig. 3B and D).

Berries were smaller with late-irrigation cutoff than with the other irrigation treatments, particularly toward later development (Fig. 3A and C). Early irrigation cutoff also resulted in smaller berries than full or deficit irrigation, but less so than late cutoffs and only during the 2nd year (Fig. 3C). Berry diameter was similar with full and deficit irrigation in either year, and was only slightly affected by crop thinning toward the latter part of development in the 2nd year (Fig. 3D).

Yield and berry weight. Neither deficit irrigation nor cutting irrigation off early had any effect on yield relative to full irrigation in 2011, but both of the treatments reduced yield in either thinned (deficit irrigation) or unthinned plants (early irrigation cutoff) in 2012 (Table 3). The late-irrigation cutoff treatment, in contrast, reduced yield each year. Fruit production often tends to be most sensitive to water deficits during later stages of fruit development as a consequence of biophysical, metabolic, and hormonal factors involved in the regulation of cell turgor and cell-wall extension (Cosgrove, 1997). However, Mingeau et al. (2001) observed similar reductions in yield by restricting water supply during early or late stages of fruit development in potted blueberry plants, suggesting that cell division during Stage I is also very sensitive to water deficits. In our case, water deficits were much more severe when irrigation was cutoff late than early, and consequently, the effects on yield were much greater.

Yield was also reduced by crop thinning in 2011 but not in 2012 (Table 3). In fact, by the 2nd year, yield was greater with than without thinning in the early irrigation cutoff treatment. However, berries from plants exposed to early irrigation cutoff weighed an average of 7% less in 2011 and 24% less in 2012 than those from the full irrigation

Table 4. Independent and combined effects of four irrigation regimes and two crop thinning strategies on fruit firmness of 'Elliott' blueberry grown in Oregon.

	Fruit firmness (g·mm^{-1})								
	2011				2012				
Treatment	Harvest 1	Harvest 2	Harvest 3		Harvest 1	Harvest 2		Harvest 3	
Irrigation			No thinning	50% crop removal		No thinning	50% crop removal	No thinning	50% crop removal
Full irrigation	166 b[z]	181 b	159 c	169 c	201	172 cd	167 cd	167 c	154 c
Deficit irrigation	177 b	184 b	173 c	178 c	205	179 c	167 cd	166 c	160 c
Early irrigation cutoff	171 b	183 b	156 c	170 c	190	168 cd	160 d	157 c	157 c
Late irrigation cutoff	221 a	345 a	362 b	452 a	215	294 b	323 a	308 b	384 a
Crop thinning									
None	177	217	202		203	203		199	
50% crop removal	184	209	226		203	204		214	
Significance									
Irrigation	**	**	**		NS	**		**	
Crop thinning	NS	NS	**		NS	NS		NS	
Irrigation × thinning	NS	NS	**		NS	*		**	

[z] Means followed by the same letter are not significantly different ($P \leq 0.05$) within a harvest date.

NS, *, ** Nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively.

Table 5. Independent and combined effects of four irrigation regimes and two crop thinning strategies on internal fruit quality of 'Elliott' blueberry grown in Oregon.[z]

	Soluble solids content (%)			Titratable acidity (% citric acid)				Sugar/acid ratio[y]			
Treatment	Harvest 1	Harvest 2	Harvest 3	Harvest 1	Harvest 2	Harvest 3		Harvest 1	Harvest 2	Harvest 3	
Irrigation						No thinning	50% crop removal			No thinning	50% crop removal
Full irrigation	13.5 b[x]	13.1 b	15.3 b	1.16 b	1.17 b	1.12 c	1.24 bc	11.6	11.3 a	12.4 a	13.6 a
Deficit irrigation	13.8 b	14.0 b	15.5 b	1.18 b	1.22 b	1.16 c	1.16 c	11.8	11.4 a	13.3 a	13.5 a
Early irrigation cutoff	12.0 c	12.7 b	12.4 c	1.11 b	1.23 b	1.45 b	1.05 c	10.9	10.4 ab	7.7 c	13.0 a
Late irrigation cutoff	18.2 a	16.9 a	18.6 a	1.68 a	1.80 a	1.86 a	2.07 a	10.9	9.5 b	9.9 b	9.3 bc
Crop thinning											
None	14.3	14.2	14.7	1.30	1.34	1.40		11.1	10.7	10.8	
50% crop removal	14.5	14.2	16.2	1.26	1.36	1.38		11.5	10.6	12.3	
Significance											
Irrigation	**	**	**	**	**	**		NS	*	**	
Crop thinning	NS	NS	**	NS	NS	NS		NS	NS	**	
Irrigation × thinning	NS	NS	NS	NS	NS	*		NS	NS	**	

[z] Data were only collected in 2012.

[y] Calculated by dividing the soluble solids content of the berries by the percentage of acid (i.e., titratable acidity).

[x] Means followed by the same letter are not significantly different ($P \leq 0.05$) within a harvest date.

NS, *, ** Nonsignificant and significant at $P \leq 0.05$ and 0.01, respectively.

treatment, and, by the 2nd year, had the same average weight as those from the late cutoff treatment (Table 3). Crop thinning, on the other hand, increased berry weight across the treatments in both years. Carbon limitations such as those induced by heavy crop loads and water deficits have been shown to negatively affect cell division, dry matter accumulation, and fruit size in tomato (*Lycopersicum esculentum* L.) and may have likewise affected the size and weight of the berries in the present study (Bertin et al., 2003; Heuvelink, 1997).

Deficit irrigation and irrigation cutoffs could also be applied after harvest. In a well-designed study, Keen and Slavich (2012) evaluated the use of postharvest deficit irrigation at 50% ET_c in southern highbush blueberry (*Vaccinium* hybrid) in Australia and found that the strategy had no effect on yield or fruit quality but reduced water use by 0.5 $ML\cdot ha^{-1}$ per year relative to full irrigation at 100% ET_c and by 1.8 $ML\cdot ha^{-1}$ per year relative to using a standard "rule of thumb" approach, whereby many growers apply 4 L/plant per day, regardless of the weather conditions. In our case, postharvest deficit irrigation at 50% ET_c would have reduced irrigation water use by an average of ≈0.25 $ML\cdot ha^{-1}$ per year relative to full irrigation. Savings from postharvest deficit irrigation or cutoffs could be particularly substantial in early and midseason northern highbush cultivars, which generally ripen a month or two earlier than Elliott. Thus, work is needed to determine whether there is any potential of using postharvest cutoffs or deficit irrigation after harvest in northern highbush blueberry.

Fruit quality and storage. Deficit irrigation had no effect on fruit firmness, soluble solids, or titratable acidity compared with full irrigation (Tables 4 and 5). Cutting off irrigation late, on the other hand, produced firmer fruit than any other treatment, particularly when the crop was thinned and the fruit were picked on the last one or two harvest dates. Enhanced firmness in this case was likely related to small fruit size (Fig. 1; Table 3). Fruit firmness is related negatively to fruit size in many crops, including blueberry (Bryla et al., 2009; Lobos et al., 2016). The late cutoff also resulted in higher fruit soluble solids and titratable acidity, which again was likely due to smaller fruit size (Dixon et al., 2015). Depriving the plants of irrigation during late stages of fruit development has been shown to increase desirable attributes such as soluble solids and acidity in a number of perennial fruit crops, including wine grape (Mathews and Anderson, 1988), peach (Li et al., 1989), and pear (Lopez et al., 2011). This is in contrast to early irrigation cutoff, which in the present study led to fruit with the lowest soluble solids on two out of the three harvest dates (Table 5). Note by the third harvest, however, that the early cutoff treatment also produced fruit with greater acidity on the nonthinned plants than either full or deficit irrigation.

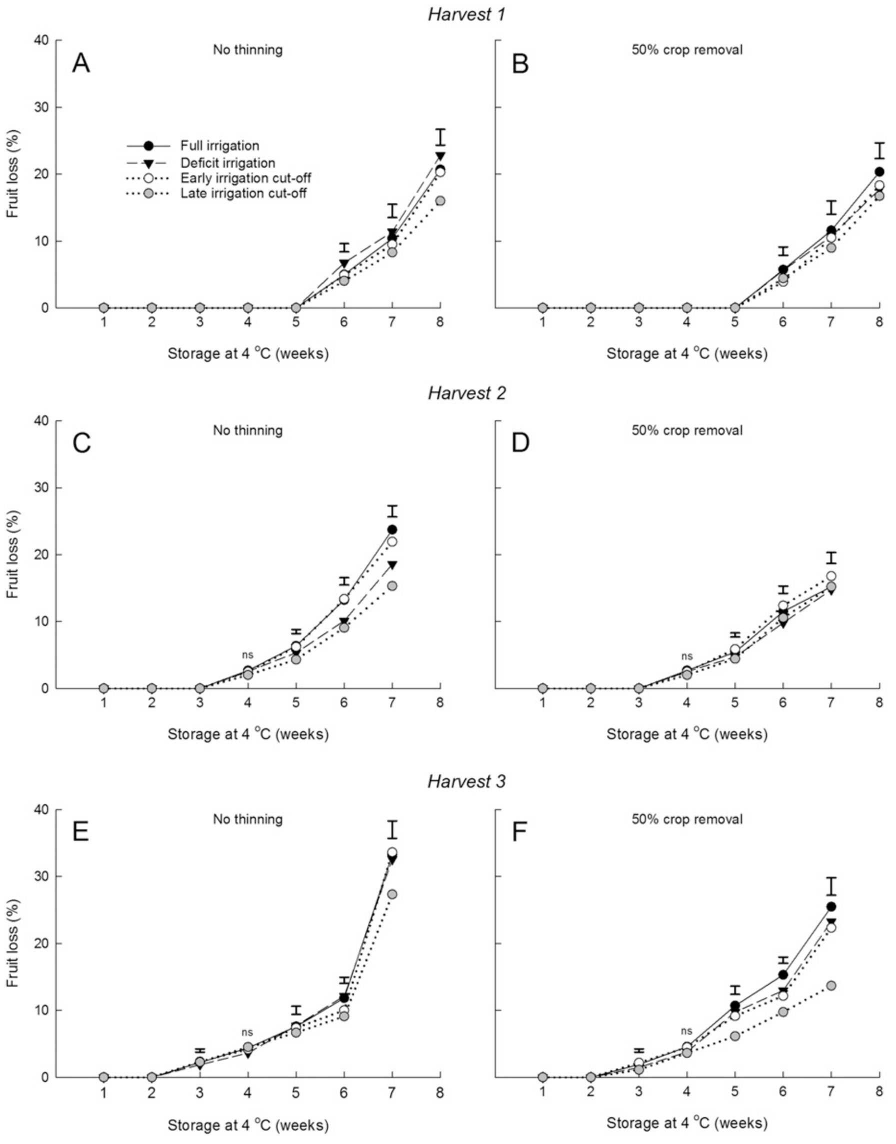

Fig. 4. Combined effects of four irrigation regimes and two crop thinning strategies on cold storage of 'Elliott' blueberry fruit. The berries were harvested on (**A**, **B**) 15 Aug., (**C**, **D**) 29 Aug., and (**E**, **F**) 13 Sept. 2012 from plants grown in Oregon with (**A**, **C**, **E**) no thinning or (**B**, **D**, **F**) 50% crop removal. Verticals bars on a given date indicate the least significant difference at $P \leq 0.05$. ns, nonsignificant.

In general, fruit with higher acidity had lower sugar/acid ratios (Table 5). However, this was not the case on the first harvest date in 2012. At that point, the ratio was similar among the treatments and was unaffected by early or late-irrigation cutoffs until the second or third harvest. The soluble solids and sugar/acid ratios measured in the present study were greater than those measured on 'Elliott' blueberry in New Jersey (Saftner et al., 2008). In their study, the berries contained only 11% soluble solids, had a sugar/acid ratio of 9.0, and received the lowest flavor score out of 12 cultivars during consumer taste tests. Sugar/acid ratio is considered one of the most important factors contributing to the flavor of blueberry (Beaudry, 1992). Although sugar/acid ratios were somewhat higher in the present study, neither deficit irrigation nor irrigation cutoff was an effective tool for increasing the ratio.

Fruit loss in cold storage varied among the treatments but, by and large, occurred faster in berries picked on the second and third harvest dates than in those picked on the first harvest date (Fig. 4). Once the fruit began to decay, losses were generally slower in fruit harvested from the late-irrigation cutoff treatment than in those harvested from fully irrigated plants. Losses were also sometimes less with deficit irrigation than with full irrigation, such as on the second harvest date (weeks 6 and 7) with no crop thinning (Fig. 4C) and on the third harvest date (week 6) with thinning (Fig. 4F). Early irrigation cutoff had a minimal effect on fruit loss during storage and only differed from full irrigation on the last harvest date (week 6; Fig. 4E and F). Using microscopy, Crisosto et al. (1994) found that deficit irrigation in peach resulted in a thicker waxy cuticle than full or excessive irrigation, which led to less water loss and shriveling in the fruit after harvest. Blueberry fruit also have a waxy bloom on the surface that seals in the moisture (Konarska, 2015) and protects the fruit against sun damage, insects, and pathogens (Riederer and Müller, 2006). It is unknown whether the thickness of wax on blueberries is affected by soil water deficit. Recently, Lobos et al. (2016) examined the use of preharvest deficit irrigation on postharvest fruit quality in 'Brigitta' northern highbush blueberry in Chile and Michigan and found that the effects of irrigation at 50% and 75% ET_c were variable, depending on the site and year, but it either had no effect or resulted in reduced fruit weight loss during 30 or 60 d of cold storage.

Conclusions

The results of this study revealed two possible options for reducing irrigation water use in northern highbush blueberry, including deficit irrigation and early irrigation cutoffs. Deficit irrigation used half as much water as full irrigation but had little to no effect on yield or fruit quality. However, deficit irrigation resulted in less vegetative growth than full irrigation, which reduced pruning labor each year but, if not managed properly, could eventually diminish fruit production. Deficit irrigation also hastened fruit ripening in one year, which depending on the cultivar, labor availability, and the market, could be an advantage or disadvantage in certain areas. For example, advancing the season of 'Elliott' would be considered a disadvantage in Oregon where this cultivar is grown for late-season fruit. Cutting off irrigation early, on the other hand, had no effect on yield the first year and delayed fruit ripening the following year. However, it decreased yield the 2nd year when the plants were unthinned and produced smaller berries with less soluble solids content than either full or deficit irrigation. Judicious use of early cutoff irrigation may be therefore warranted at times but should probably be restricted to water short years.

Cutting off irrigation late also reduced water use but produced considerably less yield than the other treatments. On average, the treatment resulted in smaller but firmer berries than full or deficit irrigation. The berries also contained higher concentrations of soluble solids and acid and lasted several days longer in cold storage. Thus, while late cutoffs reduced production, potentially deficit irrigation could be used during late stages of fruit development as a method to increase fruit quality and storage. More research is needed to find a good balance between late-season water restrictions and yield and quality in blueberry.

Crop thinning by removing fruit was laborious and showed little promise for reducing water stress during moderate or severe soil water deficits. The only advantage to crop thinning was greater vegetative growth, which, as mentioned, was important when irrigation was cutoff early to increase berry weight. Fruit bud thinning through proper pruning is essential for maintaining production and quality in northern highbush blueberry. However, it does not appear that overthinning through more severe pruning is an effective tool for mitigating drought and water restrictions.

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