AN ABSTRACT OF THE DISSERTATION OF

Khalid F. Almutairi for the degree of Doctor of Philosophy in Horticulture presented on December 2, 2016.

Title: Water and Soil Management Practices to Enhance Plant Growth, Berry Development, and Fruit Quality of Northern Highbush Blueberry (*Vaccinium corymbosum* L.)

Abstract approved:

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Bernadine C. Strik David R. Bryla

Drought and mandatory water restrictions are limiting the availability of irrigation water in many important blueberry growing regions and new strategies are needed to maintain yield and fruit quality with less water. Three potential options for reducing water use, including deficit irrigation, irrigation cut-offs, 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 cut-off for 4–6 weeks during early or late 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 cut-off early and by > 2.0 MPa when irrigation was cut-off late. In one or both years, the fruiting season was advanced with either deficit irrigation or late cut-off, whereas cutting off irrigation early delayed the season. Yield was not affected by deficit irrigation in plants with a full crop load but was reduced by an average of 35% when irrigation was cut-off late each year. Cutting off irrigation early likewise reduced yield, but only in the second year when the plants were not thinned; however, early cut-off also reduced fruit soluble solids and berry weight by 7% to 24%

compared to 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 (2.5 $ML \cdot ha^{-1}$ less water per season).

A second study was conducted in a 7-year-old field of certified organic highbush blueberry. Two cultivars (‘Duke’ and ‘Liberty’) mulched with either porous polyethylene ground cover (“weed mat”) or yard debris compost topped with sawdust (sawdust+compost) and each fertilized with either feather meal or fish emulsion were evaluated. One-year-old fruiting laterals were randomly-selected at three heights (top, middle, and bottom) on the east and west side of the plants. Bud, flower, and fruit development were monitored through fruit harvest. There was relatively little effect of mulch type or fertilizer source on the measured variables. Fruit harvest occurred ≈8 d after the fruit were fully blue and ranged from 2−25 July 2012 and 26 June−3 July 2013 in ‘Duke’ and from 1−20 Aug. 2012 and 17 July−7 Aug. 2013 in ‘Liberty’. Proportionally more fruit buds occurred on middle laterals than upper and lower laterals. The dates of bud swell and bud break were not affected by cultivar or lateral position. ‘Duke’ and ‘Liberty’ produced 6–8 and 7–9 flowers/bud, respectively. Fruit set was high in both cultivars, averaging ≈95%. However, 13–18% and 29–38 % of the initial set fruit dropped in ’Duke’ and ‘Liberty’ in late May to early June. Fruit ripening was more uniform within clusters in ‘Duke’ than in ‘Liberty’, and average fruit size was similar among harvests in ‘Duke’ but decreased by 25–40% between the first and last harvest in ‘Liberty’. Fruit matured 3−5 d earlier on the east side of the canopy than on the west side. The results suggest that pruning proportionally more on the lower part of the canopy than on the upper part will result in larger fruit at harvest than uniform pruning throughout the bush.

The final study was conducted to determine the potential of applying micronized elemental sulfur (S^o) by chemigation through the drip system to reduce high soil pH in a new planting of ‘Duke’ blueberry. The S^o was mixed with water and injected weekly for 2 months prior to planting, as well as 2 years after planting, at rates of 0, 50, 100 and 150 kg·ha^{-1} per year, and was compared to the conventional practice of incorporating prilled S^o into the soil prior to planting (two applications of 750 kg·ha^{-1} each). Chemigation quickly reduced soil pH (0-10 cm) within a month from 6.6 with no S^o to 6.1 with 50 kg·ha^{-1} S^o and 5.8 with 100 or 150 kg·ha^{-1} S^o. The change was short-term, however, and by May of the following year, soil pH averaged 6.7, 6.5, 6.2, and 6.1 with each increasing rate of S^o chemigation, respectively. The conventional treatment, in comparison, averaged 6.6 on the first date and 6.3 on the second date. In July of the following year, soil pH ranged from an average of 6.4 with no S^o to 6.2 with 150 kg·ha^{-1} S^o and 5.5 with prilled S^o. Soil pH declined thereafter to as low as 5.9 with additional S^o chemigation and at lower depths (10–30 cm) was similar to the conventional treatment. None of the treatments had any effect on winter pruning weight in year 1 or on yield, berry weight, and plant dry weight in year 2. Chemigation with S^o can be used to quickly reduce soil pH following planting and, therefore, may be a useful practice to correct high pH problems in established blueberry fields. However, it was less effective and more time consuming than applying prilled S^o prior to planting.

Water and Soil Management Practices to Enhance Plant Growth, Berry Development, and Fruit Quality of Northern Highbush Blueberry (*Vaccinium corymbosum* L.)

by
Khalid F. Almutairi

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented December 2, 2016
Commencement June 2017

Doctor of Philosophy dissertation of Khalid F. Almutairi presented on December 2, 2016

APPROVED:

Co-Major Professor, representing Horticulture

Co-Major Professor, representing Horticulture

Head of the Department of Horticulture

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Khalid F. Almutairi, Author

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my father who unconditionally supports me and helped me during my years of the program to achieve his dream and make him proud. I would like to express my sincere gratitude my mother who unconditionally loves me and wants to see me successful. I would like to express my sincere gratitude to my wife. Her encouragement, support, patience, and love through thick and thin we encountered during my program let me ot believe that "Behind every great man is a great woman".

I would like to express my sincere gratitude to my advisors, Drs. Bernadine C. Strik and David R. Bryla, for their support and guidance throughout my researches. Their continued support led me to the right way. I would also like to extend my appreciation to my committee members: Drs. Paul Schreiner, Allen Milligan, and Molly Engle for their advice during my researches. My sincere gratitude is extended to Dr. Michale Behrenfeld for his invaluable support and advice. My sincere gratitude is extended to the high Ministry of Education Saudi Arabia for a scholarship covered part of my program. Special thanks to Oscar Vargas for his help and advice throughout my researches. Special thanks to my friends Saad Alqutaimi, Emily Volmer, Amanda Vance, Mohammad Almutairi, Nawaf Almutairi, and Mohammad Alhajii for helping me collecting and analyzing data. Special thanks to Brian Yorgey, Ted Mackey, and Peter Jenkins for their help and kindness. Finally, special thanks to my family and all my friends.

CONTRIBUTION OF AUTHOR

Dr. David Bryla was involved in the experimental design, statistical interpretation of chapter two and four, and writing of chapter one, two, four and five. Dr. Bernadine Strik was involved in the experimental design, statistical interpretation and writing of chapter three.

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DEDICATION

I would like to dedicate this dissertation to my parents, the memory of my father in law (1941-2010), my mother in law, my wife, my daughter 'Ghala', my son 'Abdul Malik', and my daughter 'Lina'. Without whom, this dissertation would be impossible to achieve.

Chapter 1 – General introduction

Khalid F. Almutairi

Origin of today's blueberry

Northern highbush blueberry (*Vaccinium corymbosum* L.) belongs to the Ericaceae family and is one of four major types of cultivated blueberry. The genus has 26 species native to North America, most of which produce edible berries (Vander Kloet et al., 1988). For more than 10,000 years, native American, and then European settlers picked wild *Vaccinium* fruit and ate them fresh or dried (Holm et al., 1912; Darrow and Camp, 1945; Taylor 1974; Hawkes, 1916; Hummer, 2013). They also used the leaves and flowers for medicine (Smith, 1932; Black, 1980). The first cultivated species in the genus was cranberry (*Vaccinium macrocarpon* L.), developed by Henry Hall in 1816 (Vander Kloet et al., 1988). Blueberry was not cultivated until the early 1900's.

Commercially harvested wild blueberry had highly variable fruit size and quality, and it was difficult to establish a planting outside of the native habitat (Coville, 1910, 1916). The first attempt to produce blueberry commercially was done by conducting field experiments in Maine, Rhode Island, New York, and Michigan; however, the results were negative because the plants' soil requirements were misunderstood (Coville, 1910). In 1909, Frederick Coville of the U.S. Department of Agriculture (USDA) and a grower, Elizabeth White, started a field experiment in New Jersey. They collected germplasm of wild blueberry (*V. corymbosum*) with large fruit and superior quality for propagation, classified it, and study the plant's requiements (Coville, 1910, 1916, 1937). To this day, many hybrids of highbush blueberry are a result of the careful selections and backcrosses made during these early experiments (Galletta, 1975).

Blueberry is grown commercially worldwide and production is increasing rapidly. Approximately 86% of the total world production is located in North America and Canada (FAO, 2016). In the United States, the area planted with highbush blueberry increased from 21,618 to 34,054 ha between 2007 and 2014 (USDA, 2014). Oregon produced 11% of the total harvested area in 2014, and along with Washington is the leading producer of certified organic blueberries (Strik, 2014).

Unique soil pH requirements of blueberry

Blueberry is adapted to acidic soil conditions and prefers soil pH between 4.2 and 5.5 (Cain, 1952; Coville, 1910; Galletta, 1975; Korcak, 1988; Korcak et al., 1982; Hall et al., 1964; Harmer, 1944; Johnston, 1948; Townsend, 1966, 1967, 1969). Elemental sulfur (S^o) is often used prior to planting in higher pH soils. The So is oxidized to sulfuric acid (H_2SO_4) by chemotrophic soil bacteria (Bailey, 1978; Ballinger, 1966; Bryla et al., 2010; Camberato, 1999; Chandler et al., 1985). The processes takes time to reached the desired soil pH (Gough, 1994; Hart et al., 2003, 2006; Retamales and Hancock, 2012) and is affected by weather and soil conditions and the size of the S^o particles (Boswell and Friesen, 1993; Boswell et al., 1996; Fox et al., 1964; Hu et al., 2002; Lee et al., 1988; Germida and Janzen, 1993; Lefroy and Blair, 1997; Sholeh and Blair, 1997; Zhao et al., 2015, 2016).

Water requirements of blueberry

Blueberry plants are sensitive to water limitations due to their fibrous, shallow root system (Bryla, 2011; Eck, 1988; Freeman, 1983; Holzapfel et al., 2004; Jacobs et al., 1982; Lyrene and Williamson, 1997; Pritts and Hancock, 1992; Retamales and Hancock, 2012; Valenzuela-Estrada et al., 2008) and require irrigation in most growing regions (Bryla, 2006; Bryla and Strik, 2007; Haman et al. 1997; Holzapfel et al., 1993; Holzapfel et al., 2004). The vast majority of the roots are located at the top 50 cm of the soil (Bryla and Strik, 2007; Mingeau et al., 2001; Valenzuela-Estrada et al., 2009; Wilk et al., 2009). Bryla and Strik (2007) reported that more than 90% of fine roots are located the top 0.3 m, with the highest root density at 0.1-0.2 m. Like many members of the Ericaceae family, northern highbush blueberry lack root hairs. The finest roots are < 40 µm in diameter and are responsible for most of the water and nutrient absorption by the plants (Valenzuela-Estrada et al., 2008). The plants also form close associations with ericaceous mycorrhizal fungi (Retamales and Hancock, 2012; Jacobs et al., 1982).

Irrigation of blueberry

Overhead sprinklers and drip irrigation systems are commonly used in most commercial blueberry fields (Bryla et al., 2011; Strik and Yarborough, 2005). Drip irrigation is much more efficient than sprinklers and often leads to better plant growth and yield when a blueberry field is fertigated (Bryla and Machado, 2011; Vargas and Bryla, 2015). The amount of water applied is of course weather-dependent and varies among early, mid-, and late-season cultivars (Bryla, 2011). The effectiveness of drip can also vary with soil type. For example, Holzapfel et al. (2015) found on a sandy soil where the water holding capacity is very low that four laterals of drip per row performed better than one or two laterals per row. In sandy soils, sprinklers or micro sprinklers might be a better choice for blueberry

Plants are easily under- or over-irrigated, depending on the weather, site conditions, and the stage of plant development. Excessive irrigation reduces root function, leaches soil nutrients, and can lead to root rot (Bryla and Linderman, 2007; Bryla and Strik, 2007; de Silva et al., 1999). Over-irrigation also reduces yield and fruit quality of northern highbush blueberry (Bryla et al., 2011; Holzapfel et al., 2015). Thus, irrigation must be scheduled carefully at the proper rate in blueberry. While crop coefficients are available for irrigation scheduling in blueberry, most growers rely on plant and soil observations to decide when to irrigate.

Effects of soil water limitations on development, quality, and storage of blueberries

The most critical period of irrigation in blueberry is between fruit set and fruit harvest (Bell, 1982; Bryla, 2011, Gough, 1982; Mingeau et al., 2001). Water stress during this period reduces carbon assimilation considerably (Améglio et al., 2000) and may increase respiration of severely stressed plants (Jones and Fanjul, 1983). Growth and yield reduction can occur even under mild water deficits during fruit development in many fruit crops, including blueberry (Brightwell and Austin, 1980; Gough, 1982; Mingeau et al., 2001), peach (*Prunus persica*) (Chalmers et al., 1983), and apple (*Malus domestica*) (Lakso, 1985; Landsberg and Jones, 1981). However, carefully monitored deficit irrigation regimes are beneficial in many horticultural crops, such as raspberry (*Rubus idaeus*) and blackberry (*Rubus*) (Pascu et al., 2012), wine grape (*Vitis vinifera*) (Bravdo and Naor, 1996; McCarthy et al., 2002), apple (Ebel et al., 1995), apricot (*Prunus armeniaca*) (Ruiz-Sa´nchez et al., 2000; Pérez-Pastor et al., 2007), olive (*Olea europaea*) (Moriana et al., 2003), almond (*Prunus dulcis*) (Goldhamer and Viveros, 2000), pistachio (*Pistacia vera*) (Goldhamer and Beede, 2004), citrus (Domingo et al., 1996; Gonza´lez-Altozano and Castel, 1999; Goldhamer et al., 2000), and pomegranate (*Punica granatum*) (Intrigliolo et al., 2013).

Like many fruit crops, blueberry has a double sigmoid pattern of berry development (Eck, 1988; Edwards et al., 1970; Godoy et. al, 2008; Gough, 1993; Mingeau et al., 2001; Shimura et al.,1986; Tamada, 2002). The first stage (stage I) of fruit development occurs after fruit set and lasts from 30–45 days (Bailey, 1947; Bell, 1957; Eck, 1986; Ismail and Kender, 1974). During stage I, berry diameter and total dry weight increase through rapid cell division of the endosperm (Eck, 1986; Shutak et al., 1980). In stage II, there is little change in berry diameter or biomass as the embryos are developing (Bell, 1957). In stage III, the berry increases in size through cell enlargement via water uptake (Ismail and Kender, 1974). Fruits within a cluster of blueberries do not mature at the same time (Eck, 1986).

Stage I and III of fruit development are the most sensitive stages to water deficit due to the maximum water requirement for cell division and expansion (Bell, 1982: Gough, 1982). In apple, the first stage of fruit development has been reported to be sensitive to water deficit (Powell, 1974; Hsiao et al., 1976); however, when early water deficits were followed immediately by full irrigation, there were no effects of the deficit on vegetative growth (Bradford and Hsiao, 1982) or fruit size at harvest (Mills and Behboudian, 1996). Fruit size and quality are generally unaffected by mild to moderate drought during stage II of fruit development in peach (Chalmers et al., 1981; Girona et al., 2005; Mitchell and Chalmers, 1982) apricot (Pe´rez-Pastor et al., 2009; Torrecillas et al., 2000), and Japanese plum (*Prunus salicina*) (Samperio et al., 2015). Stage III, on the other hand, has been reported to be sensitive to drought in peach (Li et al., 1989; Crisosto et al., 1994), apple (Lotter et al., 1985) Asian pear (*Pyrus pyrifolia*) (Caspari et al., 1994), and blueberry (Mingeau et al., 2001).

Fruit quality characteristics such as firmness, color, surface wax "bloom", and other chemical components affect shelf-life and post-harvest decay in blueberry, and the berries are subject to water loss via transpiration (Wills et al., 1998). The impact of water deficit on fruit quality and postharvest characteristics is complex and variable. In apple, fruit size and percentage of soluble solids are the primary quality traits affected by water deficits (Ebel et al., 1993). Usually, fruit firmness increases as the size deceases during water deficits (Mpelasoka et al., 2000). However, Ehret et al. (2015) found recently that mild water deficits had no effect on fruit shelf life in 'Duke' blueberry. Similar results were reported in apple (Mpelasoka et al., 2001; Kilili et al., 1996). Fruit decay in blueberry increases when the berries are wet and the epidermis is damaged (Strik et al., 1993) and also occurs at the fruit scar (Ceponis and Cappellini, 1979; Lang and Tao, 1992; Cline, 1996, 1997). Advanced fruit maturation if fruit become overripe also increases infection by fungi (Ballinger et al., 1978; Miller et al., 1984) and reduces shelf-life dramatically (Ballinger et al., 1973, Mainland et al., 1975).

Objectives

The objectives of this dissertation were to: 1) evaluate the potential of using deficit irrigation, irrigation cut-offs, and crop thinning to maintain yield and fruit quality with less water; 2) evaluate the effects of cultivar (Duke and Liberty), mulch type (compost topped with sawdust and weed mat) and fertilizer source (feather meal and fish emulsion) on fruit bud and berry development within the canopy; and 3) determine the potential of applying micronized S^o by chemigation through the drip system to quickly reduce soil pH, all in northern highbush blueberry.

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Chapter 2 - Potential of Deficit Irrigation, Irrigation Cut-offs, and Crop Thinning to Maintain Yield and Fruit Quality with Less Water in Northern Highbush Blueberry

Khalid F. Alumtairi, David R. Bryla and Bernadine C. Strik

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 cut-offs, 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 cut-off 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 cut-off early and by > 2.0 MPa when irrigation was cut-off late. In one or both years, the fruiting season was advanced with either deficit irrigation or late cut-off, whereas cutting off irrigation early delayed the season. Yield was not affected by deficit irrigation in plants with a full crop load but was reduced by an average of 35% when irrigation was cut-off late each year. Cutting off irrigation early likewise reduced yield, but only in the second year when the plants were not thinned; however, early cut-off also reduced fruit soluble solids and berry weight by 7% to 24% compared to 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.

Introduction

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/week 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 on-going 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.

While 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 wine grape (*Vitis vinifera* L.), but it has not been well tested in berry crops (Fereres and Soriano, 2007; Goldhamer, 2007). The technique consists of applying less irrigation than needed [i.e., < 100% of crop evapotranspiration (ET_c)] during times when yield and quality are uncompromised or even enhanced by the water restrictions. Irrigation cut-offs may likewise be effective at reducing water use, provided the cut-offs occur during periods when water demands by the crop are low or less critical to fruit production. Pre-harvest irrigation cut-offs 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 pre-harvest irrigation in northern highbush blueberry (Bryla et al., 2009; Ehret et al., 2012; 2015). In this case, under-irrigation 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 [*P. persica* (L.) Batsch] (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 over-thinning, 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 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 cut-offs, 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. 44º33′10″ N, long. 123º13′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 $kg \cdot ha^{-1}$ of elemental S at 6 mos. and at 10 mos. prior to 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 centred 3.0-m apart. A 9-cm-deep layer of douglas fir (*Pseudotsuga menziesii* Franco) sawdust and 100 $kg \cdot ha^{-1}$ N from ammonium sulfate fertilizer were incorporated within the planting row (≈ 1.2-m wide) prior to 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 crop evapotranspiration (ET_c), deficit irrigation at 50% ET_c (applied for the entire growing season), and full irrigation with irrigation cut-off 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 over-irrigated 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 prior to 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 USA, 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 $L{\cdot}h^{-1}$ 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/). 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 bi-weekly to a depth of 0.3 m (between two plants near the center of the bed) in each non-thinned treatment, using a time domain reflectometry (TDR) 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 cut-off during early and late 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, while 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 mid-canopy 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 prior to fruit set on one representative lateral per plant in each replicate. A random sample of five berries were 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 g force (N) of compression per mm.

Approximately 150 g of berries were frozen from each replicate on each harvest date and later analyzed for soluble solids (ºBrix), 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 mol/L 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 terethphalate) 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 prior to 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 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, N.C., USA). 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 ($P < 0.05$). 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 no significant three-way interactions (irrigation, crop thinning, and harvest date).

Planned comparisons between full irrigation and other irrigation regimes were performed at the 0.05 level using Fisher's protected least significant difference (LSD) test, while 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. 2.1). 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 totalled 251 mm in 2011 and 244 mm in 2012. Potential ET, in contrast, was greatest in July to September each growing season and totalled 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. 2.1). Based on the water meter readings, 49% and 46% less water was applied each year, respectively, with deficit irrigation. The early irrigation cut-off treatment was carried out between late May and early July during the early to late-green stage of fruit development, and the late cut-off treatment was applied between late July and early September during fruit coloring and harvest. The cut-off treatments were fully irrigated at 100% ET_c during the rest of the year. Rainfall totaled 13 and 64 mm each year, respectively, during the early cut-off period and < 1 mm during the late cut-off (Fig. 2.1).

Relative to full irrigation, the early cut-off saved an average of 1.3 $ML \cdot ha^{-1}$ of water per year, while the late cut-off saved 2.3 $ML \cdot ha^{-1}$ per year. Deficit irrigation saved ≈2.5 $ML \cdot ha^{-1}$ 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 cut-off treatment and to as low as -3.0 to -3.2 MPa during the late cut-off (Fig. 2.2). Water potential declined less severely during the early cut-off due to occasional rain and lower plant water demands at that time of year (Fig. 2.1). Previously, Bryla and Strik (2007) examined weekly water deficits in three cultivars of northern highbush blueberry, including an early season cultivar, Duke, a mid-season cultivar, Bluecrop, and Elliott, and found that, regardless of the weather conditions, water potential declined most readily just prior to harvest in each of the cultivars. This was attributed to higher 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 cut-off treatment in the present study. The late cut-off treatment, on the other hand, resulted in smaller and thik leaf wilting within 2 weeks of treatment and in marginal leaf necrosis by the fourth 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% ET_c. However, when the pear trees were irrigated at 20% 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 second year (Table 2.1). Deficit irrigation generally reduces vegetative growth in many crops, including northern highbush blueberry (Bryla et al., 2011). Irrigation cut-offs, on the other hand, had no effect on pruning weight relative to full irrigation, but in this case, the treatments were only measured the second year. Crop thinning also had no effect on pruning weight the second year.

Fruit bud set varied among the treatments each year and was generally greater in plants with early irrigation cut-off than in those with full or deficit irrigation, and was lowest in plants with late irrigation cut-off (Table 2.1). Bud set was also lower with than without crop thinning the first year but not in the second 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 second year (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. 2.3). 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). Stage I and III are usually considered the most sensitive periods to water deficits (Bryla, 2011). Irrigation cut-offs 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. 2.3A). Consequently, a greater proportion of the fruit ripened earlier and were picked sooner with deficit irrigation than with full irrigation that year (Table 2.2). Deficit irrigation had no effect, however, on berry development or the timing of the fruiting season the following year. Early irrigation cut-off, in contrast, reduced the rate of berry development and delayed fruit ripening in the second year (Fig. 2.3C; Table 2.2), while cutting off irrigation in the late-season delayed early fruit development during the spring following the treatment in 2012 (Fig. 2.3C) and accelerated the harvest season in both years (Table 2.2). 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 2.2), as well as berry development, beginning at Stage II each year (Fig. 2.3B and D).

Berries were smaller with late irrigation cut-off than with the other irrigation treatments, particularly toward later development (Fig. 2.3A and C). Early irrigation cut-off also resulted in smaller berries than full or deficit irrigation, but less so than late cut-offs and only during the second year (Fig. 2.3C). 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 second year (Fig. 2.3D).

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 cut-off) in 2012 (Table 2.3). The late irrigation cut-off 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 thinning fruit in 2011, but it was not lower with the treatment when the crop was thinned by pruning flower buds in 2012 (Table 2.3). In fact, by the second year, yield was greater with than without thinning in the early irrigation cut-off treatment. However, berries from plants exposed to early irrigation cut-off weighed an average of 7% less in 2011 and 24% less in 2012 than those from the full irrigation treatment, and, by the second year, had the same average weight as those from the late cut-off treatment (Table 2.3). 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 cut-offs could also be applied after harvest. In a well-designed study, Keen and Slavich (2012) evaluated the use of post-harvest 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 $\approx$ 0.25 $ML{\cdot}ha^{-1}$ per year relative to full irrigation. Savings from post-harvest deficit irrigation or cut-offs could be particularly substantial in early and mid-season 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 post-harvest cut-offs 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 to full irrigation (Tables 2.4 and 2.5). 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. 2.1; Table 2.3). Fruit firmness is related negatively to fruit size in many crops, including blueberry (Bryla et al., 2009; Lobos et al., 2016). The late cut-off 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 cut-off, which in the present study led to fruit with the lowest soluble solids on two out of the three harvest dates (Table 2.5). Note by the third harvest, however, that the early cutoff treatment also produced fruit with greater acidity on the non-thinned plants than either full or deficit irrigation

In general, fruit with higher acidity had lower sugar to acid ratios (Table 2.5). 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 not affected by early or late irrigation cut-offs until the second or third harvest. The soluble solids and sugar to 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 to 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). While sugar-acid ratios were somewhat higher in the present study, neither deficit irrigation nor irrigation cut-off 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. 2.4). Once the fruit began to decay, losses were generally slower in fruit harvested from the late irrigation cut-off 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. 2.4C) and on the third harvest date (week 6) with thinning (Fig. 2.4F). Early irrigation cut-off had a minimal effect on fruit loss during storage and only differed from full irrigation on the last harvest date (week 6; Fig. 2.4E 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 pre-harvest deficit irrigation on post-harvest 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 cut-offs. 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 second 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 cut-off 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 cut-offs 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 cut-off early in order 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 over-thinning through more severe pruning is an effective tool for mitigating drought and water restrictions.

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Tables and Figures

Table 2.1. Independent effects of four irrigation regimes and two crop thinning strategies on fresh winter pruning weights and fruit bud set in ‘Elliott’ blueberry.

	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 cut-off	n.d.	0.77 a	48 a	50 a
Late irrigation cut-off	n.d.	0.82 a	29 c	31 c
Crop thinning				
None	—	0.73	48	40
50% crop removal	—	0.73	31	41
Significance				
Irrigation	*	*	**	**
Crop thinning	—	NS	**	NS
Irrigation × thinning	—	NS	NS	NS

[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.

n.d. – not determined.

Table 2.2. Independent and combined effects of four irrigation regimes and two crop thinning strategies on the proportion of total yield removed on each harvest date in 'Elliott' blueberry.

	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 cut-off	40 b	40 a	20 a	19 c	29 c	42 a	42 a	34 a
Late irrigation cut-off	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 2.3. Independent and combined effects of four irrigation regimes and two crop thinning strategies on yield and berry weight of 'Elliott' blueberry.

	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 cut-off	4.0 a	5.1 bc	6.4 a	1.78 b	1.33 b
Late irrigation cut-off	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.

Table 2.4. Independent and combined effects of four irrigation regimes and two crop thinning strategies on fruit firmness in ‘Elliott’ blueberry.

	Fruit firmness ($g \cdot mm^{-1}$)								
	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 cut-off	171 b	183 b	156 c	170 c	190	168 cd	160 d	157 c	157 c
Late irrigation cut-off	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 2.5. Independent and combined effects of four irrigation regimes and two crop thinning strategies on internal fruit quality of 'Elliott' blueberry in 2012.

Treatment	Soluble solids content (%)			Titratable acidity (% citric acid)				Sugar-acid ratio[z]			
	Harvest 1	Harvest 2	Harvest 3	Harvest 1	Harvest 2	Harvest 3		Harvest 1	Harvest 2	Harvest 3	
						No thinning	50% crop removal			No thinning	50% crop removal
Irrigation											
Full irrigation	13.5 b[y]	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 cut-off	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 cut-off	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]Calculated by dividing the soluble solids content of the berries by the percentage of acid (i.e., titratable acidity).

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

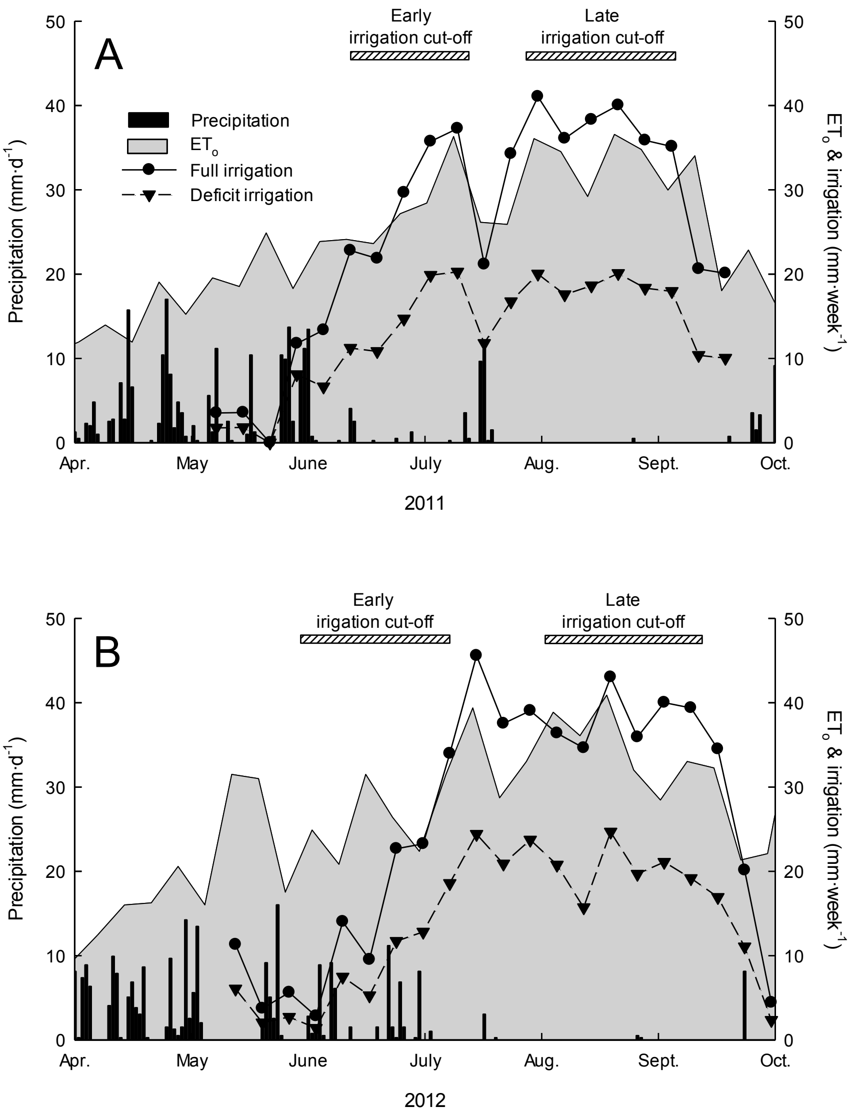

Fig. 2.1. Precipitation, potential evapotranspiration (ET_o), and irrigation applied to 'Elliott' blueberry in (**A**) 2011 and (**B**) 2012. Four irrigation regimes were applied to the plants, including full irrigation at 100% of estimated crop evapotranspiration (ET_c), deficit irrigation at 50% ET_c, and full irrigation with irrigation cut-off during early (early to late-green fruit) or late (fruit coloring to harvest) stages of fruit development.

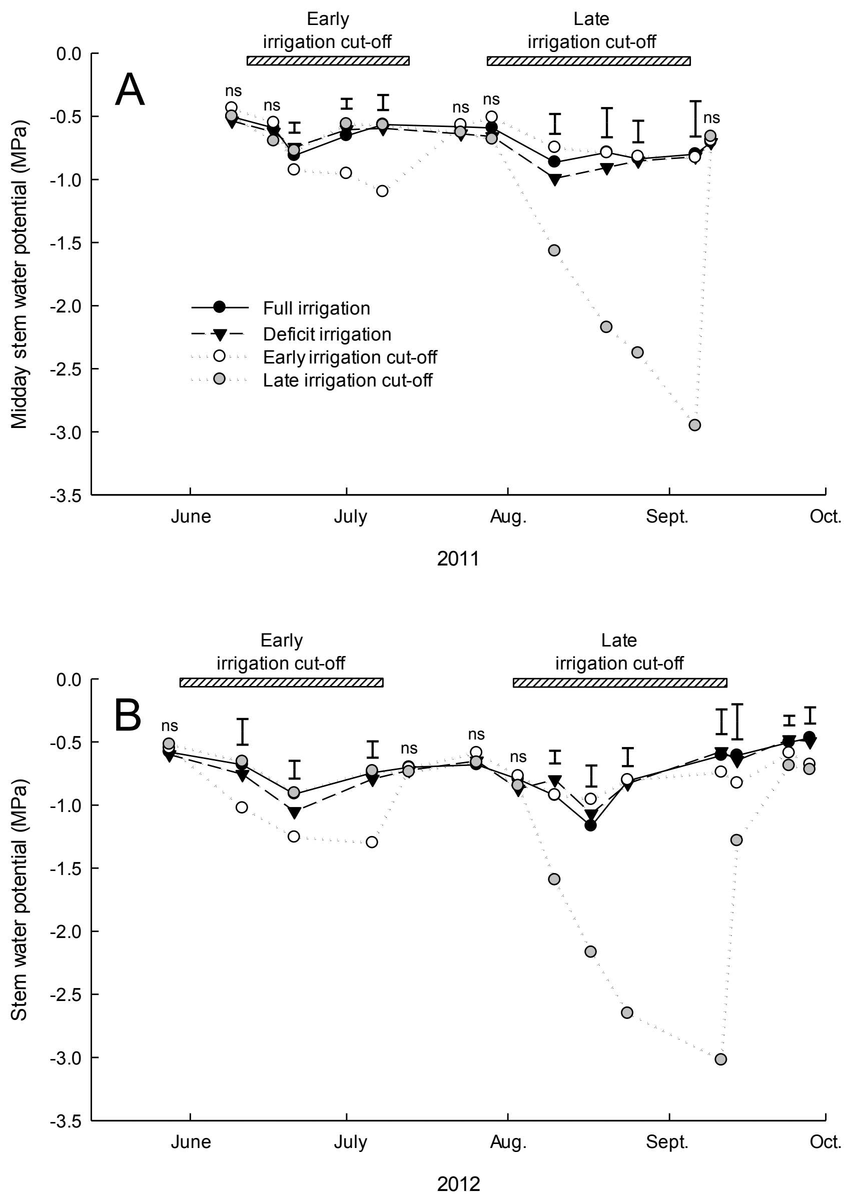

Fig. 2.2. Independent effect of four irrigation regimes on midday stem water potential of 'Elliott' blueberry in (**A**) 2011 and (**B**) 2012. The values represent the average of plants with no crop thinning. Means are separated on a given date by Fisher's protected LSD ($P \leq 0.05$); bars shown. NS – non-significant.

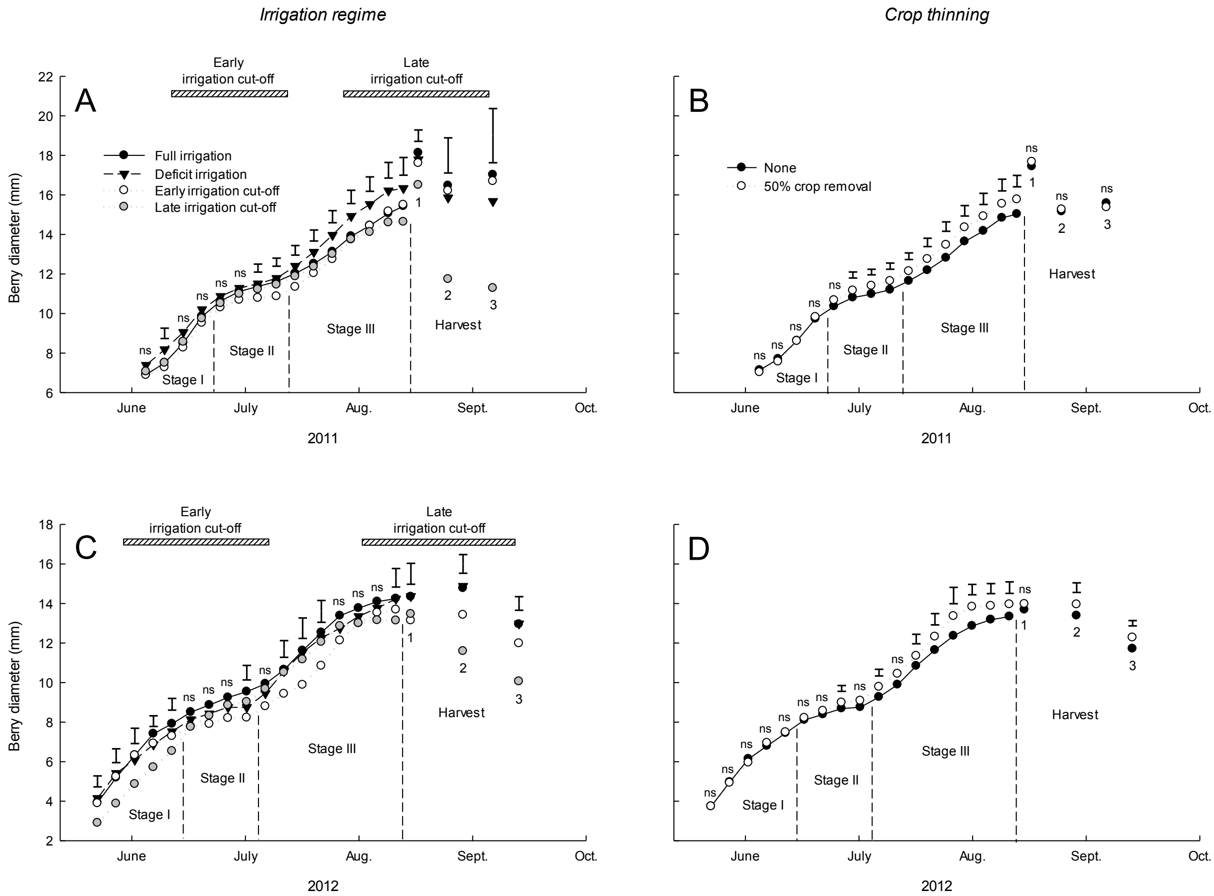

Fig. 2.3. Independent effects of (**A**, **C**) four irrigation regimes and (**B**, **D**) two crop thinning strategies on berry development of 'Elliott' blueberry in (**A**, **B**) 2011 and (**C**, **D**) 2012. Diameter was measured non-destructively prior to harvest on the same berries over time (Stage I–III) and on random samples of picked berries on each harvest date (Harvest 1–3). Means are separated on a given date by Fisher's protected LSD ($P \leq 0.05$); bars shown. NS – non-significant.

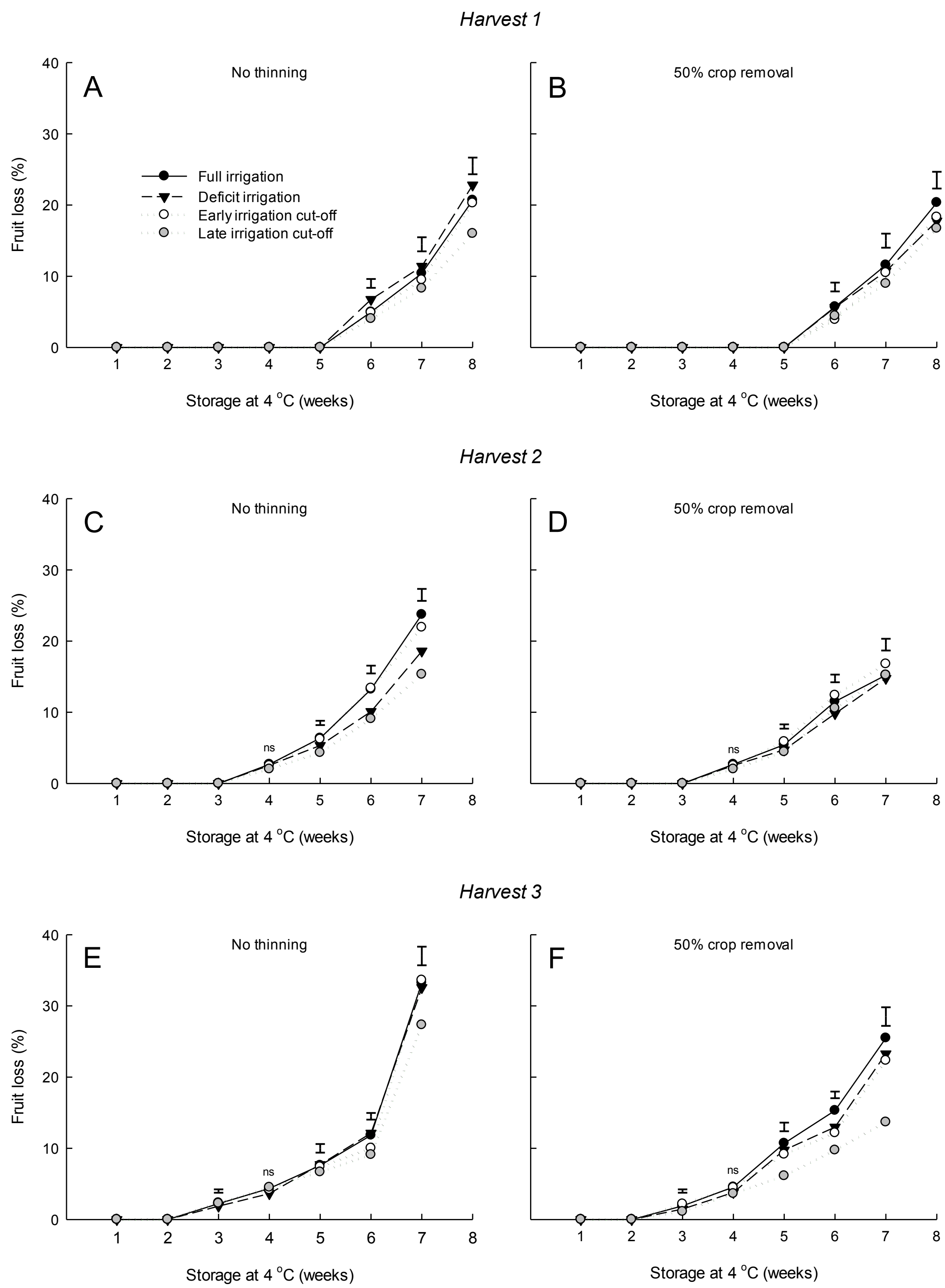

Fig. 2.4. Combined effects of four irrigation regimes and two crop thinning strategies on cold storage of ‘Elliott’ blueberry fruit. The berries were harvested on (**A**, **B**) 15 Aug., (**C**, **D**) 29 Aug., and (**E**, **F**) 13 Sept. 2012 from plants with (**A**, **C**, **E**) no thinning or (**B**, **D**, **F**) 50% crop removal. Means are separated on a given week by Fisher’s protected LSD ($P \leq 0.05$); bars shown. NS – non-significant.

Chapter 3 – Fruit Bud and Berry Development Were Affected More by Position in the Canopy Than Production System in ‘Duke’ and ‘Liberty’ Organic Blueberry

Khalid F. Alumtairi, Bernadine C. Strik, and David R. Bryla

Abstract

The study was conducted in a 7-year-old field of certified organic highbush blueberry (*Vaccinium corymbosum* L.). Plants were grown on raised beds, and treatments included 'Duke' and 'Liberty' plants mulched with porous polyethylene ground cover ("weed mat") or yard debris compost topped with sawdust (sawdust+compost) and fertilized with feather meal or fish emulsion. One-year-old fruiting laterals were randomly-selected at three heights (top, middle, and bottom) on the east and west side of the plants. The third flower bud from the distal end of each lateral was tagged, and bud, flower, and fruit development were monitored through fruit harvest. There was relatively little effect of mulch type or fertilizer source on the measured variables. Fruit harvest occurred ≈8 d after the fruit were fully blue and ranged from 2−25 July 2012 and 26 June−3 July 2013 in 'Duke' and from 1−20 Aug. 2012 and 17 July−7 Aug. 2013 in 'Liberty'. Proportionally more fruit buds occurred on middle laterals than upper and lower laterals. The dates of bud swell and bud break were not affected by cultivar or lateral position, but 'Duke' reached the early pink stage before 'Liberty'. 'Duke' and 'Liberty' produced 6–8 and 7–9 flowers/bud, respectively. Fruit set was high in both cultivars, averaging ≈95%. However, 13–18% and 29–38 % of the initial set fruit dropped in 'Duke' and 'Liberty' in late May to early June. Laterals in the upper canopy had a greater diameter (4–5 mm in 'Duke' and 2–3 mm in 'Liberty') than those in the lower canopy (2–3 and 1.5–2 mm diam. in 'Duke' and 'Liberty', respectively). The first flush of shoot growth produced only vegetative buds while the second and third flushes produced vegetative and flower buds by the following dormant period. Fruit ripening was more uniform within clusters in 'Duke' than in 'Liberty', and average fruit size was similar among harvests in 'Duke' but decreased by 25–40% between the first and last harvest in 'Liberty'. Measurements of berry diameter from fruit set to harvest every 5 d using digital imagery confirmed berry development followed a double-sigmoid curve in all treatments. Fruit matured 3−5 d earlier on the east side of the canopy than on the west side. The results suggest that pruning proportionally more on the lower part of the canopy than on the upper part will result in larger fruit at harvest than uniform pruning throughout the bush.

Introduction

The production of highbush blueberries (*Vaccinium* sp.) in the U.S.A. increased from 21,618 to 34,054 ha from 2007 to 2014 (USDA, 2014). Oregon State produced 11% of the total harvested area in 2014. Oregon and Washington have been leading the increase in certified organic area (Strik, 2014) and accounted for 20% of the total planted area in the U.S.A. in 2015 (Strik and Vance, 2016).

Cost effective weed management is considered one of the most challenging aspects of organic production. Organically-approved herbicides are limited in availability and effectiveness and have a high cost (Julian et al., 2012; Strik and Vance, 2016). The presence of weeds decreases blueberry plant growth and yield (Burkhard et al., 2009; Carroll et al., 2015; Krewer et al., 2009; Strik et al., 2009). Use of organic mulches, such as sawdust or bark, in the row area of blueberry has several benefits, including such as suppressing weedsweed suppression (Burkhard et al., 2010; Grieshop et al., 2012; Krewer et al., 2009; Larco, 2010), reducing phytophthora root rot (Downer et al., 2001; Richter et al., 2011), conserving water by as well as reducing soil evaporation from the soil surface and erosion (Fraedrich and Ham, 1982; Iles and Dosmann, 1999; Kraus, 1998; Larco et al., 2013), adding organic matter and nutrients to the soil (White, 2006), reducing soil erosion, and moderating soil temperature and fluctuations (Bussiere and Cellier, 1994; Larco et al., 2013; Mbagwu, 1991; Patriquin, 1988; Teasdale and Mohler, 1993; Qin et al., 2015; Steinmetz et al., 2016; White, 2006). Organic Consequently, organic mulches thus help tooften improve plant growth, increasing yield, and fruit quality in highbush blueberry (Albert et al., 2010; Haynes and Swift, 1986; Karp et al., 2006; Starast et al., 2002; Strik, 2014; Strik et al., 2009; Larco, 2010; Larco et al., 2013).

Three types of mulches are commonly used in commercial blueberry farms in the Pacific Northwestern (PNW) U.S.A. -- Douglas fir (*Pseudotsuga menziesii* M.) sawdust, black, porous, polyethylene ground cover ("weed mat"), and a blend of yard- or animal-based compost and sawdust (Strik, 2016; Sullivan et al., 2015). Adding yard-debris compost to a mulching program provides an excellent source of organic matter (Sullivan et al., 2015), but has increased the presence of weeds and weed control costs compared to only using sawdust (Julian et al., 2012; Strik and Vance, 2016). Compost has a low carbon to nitrogen (C:N) ratio and increases soil nutrients through the process of decomposition (Gale et al., 2006; Sikora and Szmidt, 2001; Sullivan et al., 2015).

Weed mat, approved for organic use by the USDA Organic National Program (USDA-AMS-NOP, 2011), provides excellent weed control (Strik, 2016; Strik and Vance, 2016), but associated increases in soil temperature lead to a reduction in soil organic matter over time (Steinmetz et al., 2016; Strik, 2016; Strik et al., 2012). Weed mat or compost topped with sawdust has been shown to produce a higher yield than sawdust mulch alone in northern highbush blueberry (Strik, 2016; Sullivan et al., 2015). For this reason, organic material, such as compost, may need to be added underneath the weed mat in blueberry production (Angima et al., 2011; Cogger and Sullivan, 2009; Strik, 2016).

Organic fertilizers typically provide a slow-release of nutrients and often contain many, if not all, of the essential plant macro- and micronutrients (Joseph, 2009). Fish emulsion and feather meal are the two most common commercial organic fertilizers sold in northwestern United States (Andrews et al., 2010). Fish emulsion is popular because N, P, and K are rapidly available once it is applied, and the product can be injected through a drip system and applied by fertigation (Dixon et al., 2016; Fernandez-Salvador et al., 2015; Harkins et al., 2014; Strik, 2016). Feather meal and other processed and pelletized poultry products are also excellent sources of N, but they generally release nutrients more slowly than fish emulsion because the tightly structured proteins in these products are not easily broken down by soil bacteria (Gupta and Ramnani, 2006; Hadas and Kautsky, 1994; Hartz and Johnstone, 2006; Lin et al., 1999; Onifade et al., 1998; Riffel et al., 2003; Wang, 1997). Feather meal was found to be a very effective fertilizer in a long-term study on organic blueberry (Strik, 2016).

Northern highbush blueberry is considered to be self-fertile, but cross-pollination increases percent fruit set and berry size and advances fruit maturation (Bailey, 1937; Brewer and Dobson, 1969; Eck, 1986, 1988; Eck and Mainland, 1971; Galletta, 1975; Meader and Darrow, 1947; Morrow, 1943; Shutak and Marucci, 1966; Strik et al., unpublished). While some cultivars have a high percentage of fruit set (up to 95%), other cultivars have lower fruit set due to genetic factors (Eaton, 1966; Goldy and Lyrene, 1983; Hermann and Palser, 2000; Hokanson and Hancock, 2000; Krebs and Hancock, 1988, 1990; Lang and Parrie, 1992; Vander Kloet, 1988), low pollen viability (Brewer and Dobson, 1969; Dogterom et al., 2000; Eck, 1988; Krebs and Hancock, 1991; Ratti et al., 2008; Stushnoff and Hough, 1968; Vander Kloet, 1983) or weather conditions (Peat and Goulson, 2005; Tuell and Isaac, 2010; Vicens and Bosch, 2000; Strik et al., 2014). The number of flowers per cluster is affected by cultivar (Strik et al., unpublished).

Like many fruits, blueberries have a double-sigmoid pattern of development and advance through three distinct stages (Eck, 1988; Edwards et al., 1970; Godoy et. al, 2008; Gough, 1993; Mingeau et al., 2001; Shimura et al., 1986; Tamada, 2002). Stage I occurs after fruit set and lasts from 30–45 d (Bailey, 1947; Bell, 1957; Eck, 1986; Ismail and Kender, 1974). During stage I, berry size and total dry weight increase through rapid cell division of the endosperm (Eck, 1986; Shutak et al., 1980). In stage II, there is little change in berry size or biomass as the embryos are developing (Bell, 1957). In stage III, the berries increase in size through cell enlargement via water uptake (Ismail and Kender, 1974). Fruit within a cluster of blueberries do not mature at the same time (Eck, 1986).

New shoot growth in blueberry occurs in flushes. The shoots go through a rapid growth stage, after which the apical bud aborts (“black tip” stage). Additional growth flushes then continue from axillary buds near the distal end of the shoots (Gough, 1993). There are usually 2–5 weeks between successive flushes of shoot growth. The number of flushes is dependent on the cultivar, weather conditions, and cultural practices (Gough, 1993; Shutak et al., 1980; Strik and Buller, 2005; White, 2006). The final diameter of the shoots is affected by nutrition and typically ranges from 2.5–5 mm (Gough and Shutak, 1978).

Both fruit and vegetative growth are affected by position in the canopy and often compete within the plant for light, carbohydrates, and nutrient resources (Forshey and Elfving, 1989; Hansen, 1969, 1971, 1977; Quinlan and Preston, 1971). For example, in apple [*Malus ×sylvestris* (L.) Mill. var. *domestica* (Borkh.) Mansf.], areas with limited light exposure in the tree had reduced fruit set and less fruit growth as a result of greater shoot growth in this region of the canopy (Byers et al., 1985, 1991; Jackson, 1980; Lakso, 1984, 1994; Lakso et al., 1989; Lakso and Corelli-Grappadelli, 1992; Lakso and Robinson, 1997; Palmer, 1989; Palmer and Jackson, 1977).

The objective of the present study was to evaluate the effects of mulch type and fertilizer source on fruit bud and berry development within the canopy of northern highbush blueberry. The work was conducted in a certified organic planting of 'Duke' and 'Liberty' blueberry. Both of the cultivars were mulched with either weed mat or compost topped with sawdust and were fertilized with fish emulsion or feather meal. In this long-term study, cultivar and fertilizer source have had the most impact on yield and berry size compared to mulch type. Our hypothesis was that rate of development may differ amongst some these treatments leading to differences in berry size at harvest, whereas in other treatments berries may have a faster rate of development at certain stages leading to no difference at harvest. We also hypothesized that shoots or laterals in more exposed parts of the canopy would produce more fruit buds and larger berries.

Materials and Methods

Site description. This study was conducted for 2 years (2012–2013) in a portion of a 0.4-ha planting of organic northern highbush blueberry located at Oregon State University's North Willamette Research and Extension Center (NWREC; 45°16' 47.55" N and 122°45' 21.90" W) in Aurora, OR. The planting was established in Oct. 2006 and was certified organic in 2008. Soil at the site is a Willamette silt loam (a fine-silty, mixed, superactive mesic Pachic Ultic Argixeroll) with 3% to 4% organic matter content. Plants were transplanted onto raised beds and spaced at a distance of 0.75 m within the rows and 3 m between the rows. The rows were oriented in a north-south direction. Irrigation was applied using a single lateral of drip tubing in each row and was scheduled based on precipitation and daily estimates of crop evapotranspiration obtained from a nearby Pacific Northwest Cooperative Agricultural Weather Network AgriMet weather station (http://usbr.gov/pn/agrimet/). Complete details on establishment and irrigation of the planting can be found in Larco et al. (2013).

Experimental design. Treatments were arranged in a split-split plot design with two fertilizer sources (feather meal and fish emulsion) as main plots and combinations of two cultivars (early-season ‘Duke’ and mid-season ‘Liberty’) and two mulch types [compost topped with sawdust (“sawdust+compost”) and weed mat] as subplots. Combinations of canopy exposure (east and west) and height (upper, middle, or lower) were also included in the design and treated as sub-subplot effects. Each subplot was replicated four times with one plant per replicate.

Feather meal (ranging from 11% to 13% N, depending on product or batch) and fish emulsion (4% to 5% N) were applied initially at a rate of 29 $kg \cdot ha^{-1}$ N during the first 3 years of establishment (2007–2009) and then increased incrementally to 73 $kg \cdot ha^{-1}$ N by 2013. In 2007–2013, granular feather meal was broadcast on top of the organic mulches or under the weed mat (around the base of the plants from 2007–2010 and along the row in 2011–2013); half of it was applied in March and the other half was applied in May. Fish emulsion was diluted with 10 parts water (v/v) and applied by hand as a drench around the base of the plants in 2007–2009, side-dressed with a sprayer on each side of the row in 2010, and injected through the drip system in 2011–2013 (seven equal applications every 2 weeks from mid-April to early July) (Strik, 2016).

The compost+sawdust treatment consisted of a 4-cm-deep layer of municipal yard debris compost (52 $m^3 \cdot ha^{-1}$) covered with a 5-cm-deep layer of douglas fir sawdust. The intent was to have the sawdust act as a barrier to weed seed germination in the more nutrient-rich compost layer (Strik, 2016). The compost and sawdust were applied immediately after planting in Oct. 2006 and replenished in Jan. 2011 and 2013; only the planting beds were covered. A solid, 1.5-m-wide strip of black, woven, polyethylene ground cover (TenCate Protective Fabrics; OBC Northwest Inc., Canby, OR) was centered and secured with nails over the row prior to planting the weed mat plots. The weed mat was replaced with "zippered" weed mat (overlapping pieces stapled in place on each side of the row) in the winter of 2010–2011 so that it could be opened to apply the fertilizers along the row (Strik and Vance, 2016). The properties of the mulches were characterized by Sullivan et al. (2015). Weeds were controlled, as needed, using OMRI-approved herbicides or by hand-weeding (Strik and Vance, 2016).

One representative lateral was selected from each side of the row at each canopy height from each treatment plot during bloom and counted for the number of flower and vegetative buds. The diameter (at mid-length) and length of each lateral were also measured. The third flower cluster from the distal end of each lateral was then tagged duiring bloom, and counted for the number of flowers per cluster on 25 April 2012 and 15 April 2013. The number of berries per cluster was counted at petal fall stage on 5 May 2012 and 28 April 2013 to calculate initial fruit set and then recounted on 9 June 2012 and 25 May 2013 to calculate the final percentage of fruit set.

The rate of increase in berry size was measured during development from fruit set through harvest of each year. Five flowers per cluster were marked on the gynoecium using a permanent marker. Digital images of each cluster were captured from a fixed position every 5 d using a digital camera (12.1 MP Coolpix L105, Nikon Corporation, Japan) and were later analyzed for berry size using ImageJ (Rasband, W.S., ImageJ, U. S. National Institutes of Health, Bethesda, Maryland, USA, http://imagej.nih.gov/ij/, 1997–2015). A metric ruler was placed beside the cluster in each image to provide scale. The size of five berries per cluster were averaged for each experimental unit. For statistical analysis of berry growth, the berry developmental curve was divided into the three major stages of fruit development (Bell, 1957). Stage I ranged from 25 Apr. to 25 May 2012 and 15 Apr. to 15 May 2013 in 'Duke', and from 25 Apr. to 9 June 2012 and 15 Apr. to 30 May 2013 in 'Liberty'. Stage II ranged from 30 May to 14 June 2012 and 20

May to 4 June 2013in ‘Duke’, and from 14–29 June 2012 and 9–24 June 2013 in ‘Liberty”. Stage III began at the beginning of fruit coloring and continued until the first harvest date. The berry size within each stage of development was averaged and analyzed for treatment effects.

Ripe fruit were harvested by hand approximately weekly in each plot from 2–25 July 2012 and 26 June to 3 July 2013 for ‘Duke’ and from 1–20 Aug. 2012 and 17 July to 7 Aug. 2013 for ‘Liberty’. Harvested fruit were weighed and total yield was calculated. A random sample of 25 berries per harvest was weighed to determine average berry weight, diameter, and firmness. A firmness tester (FirmTech 2; BioWorks Inc., Wamego, KS) was used to measure diameter and firmness; each berry was placed on its side on the instrument turntable, with the calyx facing inward.

Statistical analysis. Data were analyzed as a split-split-split plot design with year as the main effect, fertilizer source as the split-plot effect, combinations of cultivar and mulch type as the split-split-plot effect, and locations of canopy exposure and height as the split-split-split plot effect. Fruit development at each stage of growth was modeled using Proc GLIMMIX in SAS 9.3. Yield and fruit quality were measured and analysed for effects of cultivar, fertilizer source and mulch.

Results

Weather conditions. Weather conditions were warmer and drier in 2013 than in 2012 (Table 3.1), which advanced fruit development the second year (Fig.1). For example, the berries in ‘Duke’ were the same size in mid-April in 2013 as they were in late April in 2012. The length of the 2012 and 2013 fruiting seasons were 90 and 85 d, respectively, in ‘Duke’, and 115 and 105 d, respectively, in ‘Liberty’.

Lateral development. The total number of buds per lateral was significantly affected by various interactions among year, fertilizer source, mulch type, cultivar, and canopy height (Table 3.2). In general, the number of buds on the laterals decreased with canopy height in both cultivars and were greater on east side than on west side of the canopy in 'Duke' but on the opposite side of the canopy in 'Liberty'.

Fruit bud set was greater in 2012 than in 2013, increasing by an average of 6.1% in 'Duke' and 2.3% in 'Liberty', respectively, and was also affected by mulch, cultivar, and canopy height, with several significant interactions among treatments (Table 3.3). 'Duke' had a greater average percent fruit bud set (44.8) than 'Liberty' (39.5). Feather meal increased fruit bud set in 'Duke' an average of 10.4% compared to fish emulsion, whereas feather meal decreased percent bud set (7%) in 'Liberty' for the two seasons. Plants mulched with weed mat had a greater fruit bud set (47.9%) than those mulched with sawdust+compost (46.9%), on average. In 'Duke', weed mat increased the fruit bud set by 9.7% and 6.1% compared to sawdust+compost in 2012 and 2013, respectively. On the other hand, in 'Liberty', weed mat decreased fruit bud set by 4.4% and 2.9% compared to sawdust+compost in 2012 and 2013, respectively.

On average, laterals were thicker in 'Duke' than in 'Liberty' (Table 3.4). Weed mat increased average lateral diameter compared to sawdust+compost in both cultivars. In 'Duke', there was no effect of year when weed mat was used, whereas laterals had 5% less diameter in 2013 than 2012 with sawdust+compost mulch. In contrast, there was no year effect on lateral diameter in 'Liberty' with sawdust+compost mulch, whereas plants with weed mat produced thicker laterals in 2012 (3.5 mm) than in 2013 (3.4 mm). In 'Duke', fertilization with fish emulsion led to thicker laterals than when feather meal was used. Lateral position in the canopy was a key factor in lateral thickness for both cultivars as laterals in the upper canopy were thicker than those in the mid- and lower canopy positions. Canopy exposure had no impact on lateral diameter (Table 3.4).

Flower number and fruit set. 'Duke' had fewer flowers/cluster and a greater percent fruit set than 'Liberty' and there were fewer flowers/cluster in 2013 than in 2012 (Table 3.5). The percentage of fruit set as determined immediately after petal fall (late April or early May) was affected only by cultivar and averaged 96% and 94.6% in ‘Duke’ and ‘Liberty’, respectively (data not shown). However, there was more fruit drop in ‘Liberty’ than in ‘Duke’, leading to a significantly lower final fruit set in ‘Liberty’ (Table 3.5). The final fruit set in ‘Duke’ was lower in 2012 (79.6%) than in 2013 (84.5%), whereas in ‘Liberty’ fruit set was higher in 2012 (68.5%) than in 2013 (65.6%).

Plants grown with weed mat had more berries/cluster and a higher percent fruit set than those grown with sawdust+compost (Table 3.5). In addition, plants mulched with weed mat had more berries/cluster on laterals located in the upper or mid-canopy in 2012 and 2013, respectively. In contrast, plants mulched with sawdust+compost had more berries/cluster on laterals located in the mid- and lower canopy in 2012 and 2013, respectively (data not shown). Fruit set was greater in clusters located in the lower and mid-canopy in 2012 and 2013, respectively, for plants mulched with weed mat. However, when plants were mulched with sawdust+compost, clusters in the mid- and lower canopy had the highest fruit set in 2012 and 2013, respectively (data not shown).

There was no main effect of fertilizer source on the number of flowers or berries/cluster or fruit set (Table 3.5). While there was a significant interaction between cultivar, fertilizer source and canopy location on fruit set, there was no consistent effect.

In ‘Liberty’, the highest fruit set was found on mid-canopy laterals in 2012 and upper laterals in 2013 when fertilized with fish emulsion, whereas plants fertilized with feather meal had the highest fruit set on mid-canopy laterals in 2012 and lower laterals in 2013 (data not shown). In ‘Duke’, plants fertilized with feather meal had the highest fruit set in the mid-canopy in both years, whereas upper-canopy (2012) and lower (2013) laterals had higher fruit set when plants were fertilized with fish emulsion.

Shoot growth. The first shoot growth flush produced only vegetative buds while the second and third flushes produced vegetative and flower buds (data not shown). The number of flushes of growth and shoot length were greater for laterals on the west side of the bush than the east in 'Duke', whereas the opposite was found in 'Liberty' (Table 3.6).

Berry development. The dates of bud swell and bud break (10–15 Mar.) were similar between the cultivars and unaffected by lateral position (exposure or height) in 2012 and 2013. However, 'Duke' reached the early pink stage ≈5 d earlier in mid-to-late March than 'Liberty'.

Berry growth was affected by a number of treatment factors at each stage of development, including various interactions among year, fertilizer, cultivar, mulch, and canopy exposure and height (Table 3.7). The beries time from fruit set to harvest was 5 and 15 d longer in Both cultivars had a double-sigmoid pattern of berry development (Fig. 3.1). There was a significant year by cultivar interaction on berry size in each of Stage II and III. The early, warm spring in 2013 (Table 3.1) advanced fruit development in 'Duke' and reduced the time from fruit set to first harvest by 5 d in 'Duke' and 15 d in 'Liberty' (Fig. 3.1). The Lag Phase or Stage II of fruit development in 'Duke' lasted about 15–20 d compared to 20–25 d in 'Liberty'. Stage I and II were similar in the 2012 and 2013 for 'Duke' as they were 35 d and 20 d, respectively. However, in 2012, Stage III was 25 d, compared to 20 d in 2013. In contrast, the length of each stage of berry development was similar between years for 'Liberty', 40, 30, and 25 d for Stage I, II, and III, respectively. In both cultivars, Stage I lasted the longest and Stage III the shortest.

Plants fertilized with fish emulsion had a lower average berry diameter when mulched with weed mat than with sawdust+compost (Fig. 3.2A). However, when fertilized with feather meal, plants mulched with weed matt had larger berries in Stage II and III than those mulched with sawdust+compost (Fig. 3.2B). In addition, plants fertilized with feather meal had larger berries in the latter part of Stage I and in Stage II and III in clusters with an eastern exposure, whereas the opposite was found in Stage I and III for those fertilized with fish emulsion (Fig. 3.3). During Stage I of fruit development, the middle clusters from the west side had a greater average fruit diameter (7.1 mm) than those in clusters at a similar height on the east side (6.8 mm) (data not shown). However, in Stage II, berries from upper laterals were larger on the east side (8.2 mm) than on the west side

(8.0 mm). Thus, berries on the east side of the bush were at the fully blue stage about 5–6 d before those on the west side.

The impact of canopy height on berry development within the clusters was affected by an interaction of mulch and cultivar in Stage II and III (Table 3.7). Canopy height had more effect on berry size in ‘Duke’ than in ‘Liberty’ (Fig. 3.4). In ‘Duke’ during Stage II and III, berries in lower clusters were smaller than those in upper clusters when plants were mulched with weed mat and were smaller when located in the lower or mid-canopy as compared to the upper canopy when mulched with sawdust+compost (Fig. 3.4A and B). In contrast, there was relatively little impact of canopy height on berry development in ‘Liberty’ with upper clusters only having larger berries in Stage III when plants were mulched with sawdust+compost (Fig. 3.4 D).

There was also an interaction of canopy height, fertilizer source and cultivar on berry diameter in Stage II and III (Table 3.7). In ‘Duke’, berries in lower clusters were smaller than those in middle or upper clusters when fertilized with fish emulsion (Fig. 3.5A), whereas in ‘Liberty’ berries in mid-canopy clusters were smallest in Stage III when fertilized with fish emulsion (Fig. 3.5C). When plants were fertilized with feather meal, berries were largest in upper clusters in Stage III for ‘Liberty’ (Fig. 3.5D), but fertilizer source had relatively little effect on berry development in ‘Duke’ (Fig. 3.5B).

Yield and fruit quality. Yield averaged 2.5 kg/plant in ‘Duke’ and 3.9 kg/plant in ‘Liberty’, which is typical for plants of this age in Oregon. Berry size was also typical and, depending on the treatment and harvest date, averaged 18.1–18.4 mm diameter in ‘Duke’ and 16–21 mm diameter in ‘Liberty’. The largest berries were produced with combinations of sawdust+compost and feather meal in ‘Duke’ (18.6 mm) and weed mat and fish emulsion in ‘Liberty’ (18.7 mm).

Berry firmness decreased slightly over the harvest season in both cultivars but was greater in ‘Duke’ than in ‘Liberty’ during years of the study. From first to last harvest, berry firmness of ‘Duke’ dropped from 178 to 164 $g \cdot mm^{-1}$ in 2012 and from 194 to 161 $g \cdot mm^{-1}$ in 2013, while berry firmness of 'Liberty' dropped from 159 to 157 g·mm^{-1} in 2012 and from 155 to 152 g·mm^{-1} in 2013. Berry weight averaged 2.3–2.4 g each year in 'Duke' and 2.30 g each year in 'Liberty'.

Discussion

Flower bud initiation (FBI) and differentiation (FBD) are complicated in northern highbush blueberry and affected by cultivar differences (Strik and Vance, 2014), shoot growth (Bañados, 2006; Bañados and Strik, 2006), endogenous hormones (Black and Ehlenfeldt, 2007; Ehlenfeldt, 1998; Retamales et al., 2000), environmental conditions (Bañados and Strik, 2006; Pescie et al., 2011; Spann et al., 2004), pruning (Jorquera-Fontena et al., 2014; Kovaleski et al., 2015; Strik et al., 2003), fertilizer (Percival and Sanderson, 2004; Smagula and Kreider, 2008; Swain and Darnell, 2001; Yadong et al., 2009), crop load (Almutairi et al., 2016; Ehlenfeldt, 1998; Jorquera-Fontena et al., 2014), plant water status (Almutairi et al., 2016; Bryla et al., 2011; Mingeau et al., 2001), and mulch type (Haynes and Swift, 1986). Flower bud initiation in northern highbush blueberry began in late summer and early fall, under short daylength, while FBD continued through the late winter and early spring (Bañados and Strik, 2006).

High fruit bud set is critical to profitable production in northern highbush blueberry. In general, fruit bud set was greater with feather meal than with fish emulsion in Duke, but in Liberty, it was greater with fish emulsion. Fish emulsion breaks down much faster than feather meal. Too much N may have been available during flower bud initiation in the early season cultivar, Duke, than in the mid-season cultivar, 'Liberty'. High N tends reduces fruit bud set in many crops, including northern highbush blueberry. Yield is also lower with fish emulsion than with feather meal in 'Duke' (Strik, 2016).

Fruit bud set was also affected by canopy height. In general, fruit bud set was greater on the upper laterals than on the lower laterals. Yáñez et al. (2009) observed a similar decrease in fruit bud set from the top to the lower part of the canopy in rabbiteye blueberry (*V. virgatum* Aiton). In the present study, upper laterals were thicker than the lower laterals, on average, and fruit bud set is greater on thicker laterals in blueberry (Gough et al., 1976). We speculate that this was a result of more light exposure in the upper laterals. Photo-selective shade nets reduced the number of flower buds in 'Elliott' blueberry, proportionally to the level of shade (Lobos et al., 2013).

The higher cumulative yield (4%) of weed mat as compared to sawdust+compost in an eight-year study in this field (Strik, 2016), may be a result of the higher fruit bud set we measured in this study. Date of bud break overlapped in the two cultivars studied, but 'Duke' reached the full bloom stage before 'Liberty' in both seasons, agreeing with Kirk and Isaacs (2012) who reported that bloom date of five northern highbush blueberry cultivars overlapped under field conditions.

'Liberty' had more flowers per cluster than 'Duke', but flower number was also affected by year agreeing with earlier reports (Strik and Vance, 2014). While we found that fruit set was high, as have others in this region (Strik and Vance, 2014), this is the first report of fruit drop in 'Liberty' leading to a significantly lower ultimate fruit set. Cultivar had the largest impact on fruit set. Fertilizer source interacted with exposure and/or canopy height impact to influence fruit set. In general, the percentage of fruit set increased with apparent sun light exposure when plants were fertilized with fish emulsion in 'Liberty' and feather meal in 'Duke'.

To the best of our knowledge, this is the first field experiment in a horticultural crop where ImageJ software was used to measure fruit development instead of the conventional method (digital caliper; e.g., Almutairi et al., 2016). By using this new method, we were able to measure a large number of berries (960) *in situ* to frequently measure berries, non-destructively from fruit set to harvest. We thus confirmed that development of berry size followed a double sigmoid curve (Almutairi et al., 2016; Jorquera-Fontena et al., 2014). Despite the various treatments studied, the berry developmental curves looked very similar. Year, cultivar and cluster height had the most influence on development of berry size, whereas fertilizer source and canopy height affected average berry size in various stages of development, but not the shape of the fruit developmental curve.

The average number of days from fruit set to first harvest for ‘Duke’ was 80 and 75 in 2012 and 2013, respectively, whereas ‘Liberty’ took 95 d in both years. Thus, the slight increase in mean and maximum air temperature may have influenced and enhanced fruit development in ‘Duke’ more than in ‘Liberty’.

Overall, cluster location influenced final berry size in ‘Duke’ more than in ‘Liberty’ in both seasons. Shaded clusters produced smaller berries that took longer to ripen than those fully or partially exposed to sun light, agreeing with Hindle et al., (1957) and Young (1952) in blueberry and Dokoozlian and Kliewer (1996) in grapes. However, in grapes, cluster exposure had no impact on berry dry weight (Kliewer, 1977; Kliewer and Antcliff, 1970; Kliewer and Lider, 1968; Macaulay and Morris, 1993; Morrison, 1988; Reynolds et al., 1986). It is possible that the treatment effects on berry size we observed were due to berry moisture content; we did not measure dry weight. Light exposure increased the weight and diameter of grape berries compared to those in the shade during the initial stages of fruit development (Dokoozlian, 1996) due to perhaps the influence of light on the concentration of phytohormones (Coombe, 1973). In contrast, clusters of grapes exposed to full sunlight produced smaller berries than shaded ones (Crippen and Morrison, 1986; Kliewer and Lider, 1968; Reynolds et al., 1986) due to excessive light raising berry temperature above those optimumal for berry growth (Hale and Buttrose, 1974; Reynolds et al., 1986). The impact of berry temperature on growth has not been studied in blueberry. We did observe that the average maximum air temperature during the first stages of fruit development was 19.7 and 20.7 °C in May 2012 and 2013, respectively. This slight increase in air temperature may have had a minimum impact on season length in ‘Duke’ but not ‘Liberty’. However, when the season progressed and canopy growth resumed after fruit set, the lower clusters were observed to be shaded by leaves more than the middle or upper clusters; this may have accounted for the greater reduction in ‘Liberty’ berry size over the season, since most of the berries from the last harvest were from the lower clusters. Hole and Scott (1981) suggested that shading grape fruit during the first stage of development may permanently reduce sink strength in grapes. It is unclear if that is also an issue in blueberry.

In summary, cultivars differed in the response of fruit bud set to fertilizer source and mulch type. Nevertheless, the proportion of fruit buds was affected by the location of the lateral in the canopy (height and exposure). Laterals in the upper canopy tended to be more vigorous and had a greater diameter than those in the mid- and lower canopy. The pattern or shape of the berry developmental curve was not affected by the treatments we studied, even though these treatments affected average size at various stages of fruit development. There was relatively little effect of mulch type or fertilizer source on the measured variables. While 'Liberty' had more flowers/bud than 'Duke', 'Liberty' had a higher percentage of berry drop in June (during stage I of fruit development) resulting in a lower final fruit set. Fruit development within clusters was more uniform in 'Duke' than in 'Liberty' which resulted in relatively uniform fruit size among harvests in 'Duke' as compared to 'Liberty'. The smaller berries, located in lower clusters and picked during the last harvest of 'Liberty' took longer to mature than in 'Duke'Our results suggest that pruning proportionally more on the lower part of the canopy with keeping the canopy open will result in larger fruit at harvest than uniform pruning throughout the bush. Nevertheless, lees pruning on the upper canopy will shade the lower parts and delayed the harvest with smaller fruits.

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Tables and Figures

Table 3.1. Mean daily average, minimum, and maximum air temperature and total precipitation April. to Oct. 2012–13 at the North Willamette Research and Extension Center, Aurora, OR.

	Mean air Temp. (°C)			Minimum air Temp. (°C)			Maximum air Temp. (°C)			Precipitation total (mm)		
Month	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
March	7.72	7.1	8.8	4.55	2.9	3.8	11.54	11.6	14.0	176	226	60
April	8.27	11.0	11.2	3.83	5.8	5.9	12.92	16.4	16.5	123	106	54
May	11.39	13.5	14.6	6.84	7.4	8.9	16.48	19.7	20.7	88	78	110
June	15.8	15.5	17.7	11.02	10.2	11.2	20.86	21.1	22.4	26	67	33
July	18.39	19.3	20.5	11.91	12.5	12.4	24.94	26.9	29.0	29	13	0
August	19.89	20.4	20.7	13.11	12.3	14.0	27.1	29.2	28.0	2	0	14
September	18.53	17.6	17.1	11.49	9.0	12.5	26.25	26.3	22.9	19	3	191
October	12.04	12.8	10.8	8.44	7.6	5.1	16.21	18.3	17.5	61	169	26
Total/Avg.	14.00	14.7	15.2	8.90	8.5	9.2	19.54	21.2	21.4	525	662	488

Data were obtained from a nearby AgriMet weather station (Aurora, OR) (U.S. Department of the Interior, 2013).

Table 3.2. Impact of mulch (weed mat and sawdust + compost), fertilizer source (fish emulsion and feather meal), canopy exposure (east and west side), and canopy height (upper, middle, and lower) on total buds of 'Duke' and 'Liberty' blueberry in 2012 and 2013 (n = 4).

	Total buds (No./lateral)[z]											
	Duke						**Liberty**					
	2012			**2013**			**2012**			**2013**		
Treatment	**East**	**West**	**Difference**	**East**	**West**	**Difference**	**East**	**West**	**Difference**	**East**	**West**	**Difference**
Weed mat												
Fish emulsion												
Upper canopy	20	20	0	18	17	1	17	16	1	15	18	-3
Middle canopy	14	14	0	15	15	0	17	18	-1	15	17	-2
Lower canopy	12	13	-1	12	12	0	13	13	0	12	11	1
Avg	15	16		15	15		16	16		14	15	
Feather meal												
Upper canopy	25	20	5	23	19	4	18	24	-6	19	22	-3
Middle canopy	19	13	6	17	15	2	23	22	1	13	20	-7
Lower canopy	11	12	-1	14	14	0	11	13	-2	12	11	1
Avg	18	15		18	16		17	20		15	18	
Sawdust + compost												
Fish emulsion												
Upper canopy	21	21	0	21	19	2	16	20	-4	19	19	0
Middle canopy	19	17	2	17	16	1	14	19	-5	16	16	0
Lower canopy	14	14	0	14	13	1	12	11	1	10	12	-2
Avg	18	17		17	16		14	17		15	16	
Feather meal												
Upper canopy	16	15	1	23	17	6	20	29	-9	18	26	-8
Middle canopy	12	13	-1	17	15	2	30	19	11	23	16	7
Lower canopy	10	11	-1	14	14	0	13	12	1	14	13	1
Avg	13	13		18	15		21	20		18	18	

[z]Total buds was significantly affected by year ($P \leq 0.05$), fertilizer ($P \leq 0.001$), mulch ($P \leq 0.001$), cultivar ($P \leq 0.001$), height ($P \leq 0.001$), year x mulch ($P \leq 0.01$), year x cultivar ($P \leq 0.001$), fertilizer x cultivar ($P \leq 0.001$), fertilizer x mulch ($P \leq 0.01$), mulch x cultivar ($P \leq 0.01$), fertilizer x exposure ($P \leq 0.01$), cultivar x exposure ($P \leq 0.001$), year x height ($P \leq 0.01$), fertilizer x height ($P \leq 0.001$), cultivar x height ($P \leq 0.001$), exposure x height ($P \leq 0.001$), year x fertilizer x mulch ($P \leq 0.05$), year x fertilizer x cultivar ($P \leq 0.001$), fertilizer x mulch x cultivar ($P \leq 0.01$), year x mulch x exposure ($P \leq 0.01$), fertilizer x cultivar x exposure ($P \leq 0.05$), mulch x cultivar x exposure ($P \leq 0.05$), year x fertilizer x height ($P \leq 0.001$), fertilizer x mulch x height ($P \leq 0.001$), year x cultivar x height ($P \leq 0.001$), fertilizer x cultivar x height ($P \leq 0.001$), mulch x cultivar x height ($P \leq 0.001$), year x exposure x height ($P \leq 0.05$), fertilizer x exposure x height ($P \leq 0.001$), mulch x exposure x height ($P \leq 0.001$), cultivar x exposure x height ($P \leq 0.001$), mulch x cultivar x exposure x height ($P \leq 0.001$), year x fertilizer x mulch x cultivar ($P \leq 0.01$), fertilizer x mulch x cultivar x exposure ($P \leq 0.001$), year x mulch x cultivar x height ($P \leq 0.05$), year x fertilizer x exposure x height ($P \leq 0.01$), year x mulch x exposure x height ($P \leq 0.01$), fertilizer x mulch x exposure x height ($P \leq 0.01$), fertilizer x cultivar x exposure x height ($P \leq 0.001$), year x fertilizer x mulch x cultivar x exposure ($P \leq 0.01$), year x fertilizer x cultivar x exposure x height ($P \leq 0.01$), fertilizer x mulch x cultivar x exposure x height ($P \leq 0.001$), and year x fertilizer x mulch x cultivar x exposure x height ($P \leq 0.05$).

Table 3.3. Impact of mulch (weed mat and sawdust + compost), fertilizer source (fish emulsion and feather meal), canopy exposure (east and west side), and canopy height (upper, middle, and lower) on fruit bud set of 'Duke' and 'Liberty' blueberry in 2012 and 2013 (n = 4).

	Fruit bud set (%)[z]											
	Duke						Liberty					
	2012			2013			2012			2013		
Treatment	**East**	**West**	**Difference**	**East**	**West**	**Difference**	**East**	**West**	**Difference**	**East**	**West**	**Difference**
Weed mat												
Fish emulsion												
Upper canopy	45	40	5	33	35	-2	29	31	-2	33	33	0
Middle canopy	57	57	0	53	53	0	41	50	-9	47	47	0
Lower canopy	58	54	4	67	58	9	62	54	8	58	55	3
Avg	53	50		51	49		44	45		46	45	
Feather meal												
Upper canopy	56	45	11	52	47	5	28	33	-5	32	32	0
Middle canopy	47	54	-7	47	53	-6	39	41	-2	38	40	-2
Lower canopy	64	67	-3	64	50	14	55	62	-7	50	55	-5
Avg	56	55		54	50		41	45		40	42	
Sawdust + compost												
Fish emulsion												
Upper canopy	43	38	5	33	37	-4	38	40	-2	32	32	0
Middle canopy	32	41	-9	41	44	-3	43	58	-15	38	50	-12
Lower canopy	64	57	7	57	54	3	58	64	-6	60	58	2
Avg	46	45		44	45		46	54		43	47	
Feather meal												
Upper canopy	44	53	-9	52	41	11	45	38	7	39	31	8
Middle canopy	50	46	4	47	53	-6	50	32	18	52	38	14
Lower canopy	60	64	-4	64	50	14	46	42	4	57	46	11
Avg	51	54		54	48		47	37		49	38	

[z]Fruit bud set was significantly affected by year ($P \leq 0.01$), mulch ($P \leq 0.05$), cultivar ($P \leq 0.001$), height ($P \leq 0.001$), year x exposure ($P \leq 0.05$), year x height ($P \leq 0.05$), mulch x cultivar ($P \leq 0.001$), mulch x height ($P \leq 0.001$), fertilizer x cultivar ($P \leq 0.001$), fertilizer x exposure ($P \leq 0.01$), fertilizer x height ($P \leq 0.001$), cultivar x height ($P \leq 0.001$), exposure x height ($P \leq 0.001$), year x mulch x fertilizer ($P \leq 0.05$), year x mulch x height ($P \leq 0.05$), year x exposure x height ($P \leq 0.05$), mulch x fertilizer x cultivar ($P \leq 0.01$), mulch x fertilizer x exposure ($P \leq 0.001$), mulch x fertilizer x height ($P \leq 0.001$), mulch x cultivar x exposure ($P \leq 0.05$), mulch x cultivar x height ($P \leq 0.001$), fertilizer x cultivar x exposure ($P \leq 0.05$), fertilizer x exposure x height ($P \leq 0.01$), mulch x cultivar x exposure ($P \leq 0.05$), mulch x cultivar x height ($P \leq 0.001$), year x fertilizer x mulch x height ($P \leq 0.05$), year x fertilizer x cultivar x exposure ($P \leq 0.05$), year x fertilizer x cultivar x height ($P \leq 0.05$), year x fertilizer x exposure x height ($P \leq 0.01$), year x mulch x cultivar x height ($P \leq 0.001$), fertilizer x mulch x cultivar x exposure ($P \leq 0.001$), fertilizer x mulch x cultivar x height ($P \leq 0.001$), fertilizer x mulch x exposure x height ($P \leq 0.01$), and fertilizer x cultivar x exposure x height ($P \leq 0.01$).

Table 3.4. Impact of mulch (weed mat and sawdust + compost), fertilizer source (fish emulsion and feather meal), and canopy height (upper, middle, and lower) on lateral diameter of 'Duke' and 'Liberty' blueberry in 2012 and 2013 (n = 4).

Treatment	**Lateral diameter (mm)**	
Mulch		
Weed mat	3.9	
Sawdust + compost	3.7	
Fertilizer source	Duke	Liberty
Fish emulsion	4.3	3.4
Feather meal	4.0	3.5
Canopy height	2012	2013
Upper	3.8	4.0
Middle	3.8	3.7
Lower	3.7	3.4

[z]Lateral diameter was significantly affected by mulch ($P \leq 0.05$), cultivar ($P \leq 0.001$), height ($P \leq 0.001$), year x height ($P \leq 0.001$), and fertilizer x cultivar ($P \leq 0.05$).

Table 3.5. Impact of cultivar and mulch on the number of flowers and berries per cluster and percent fruit set in certified organic northern highbush blueberry grown at the North Willamette Research and Extension Center, Aurora, OR in 2012 and 2013 (March, 2012-2013; averaged over year, fertilizer source, exposure, and canopy height, when non-significant main effect).

Treatments[z]		Flowers/cluster[y] 2012	Flowers/cluster[y] 2013	Berries/cluster[x]	Fruit set (%)
Duke	Weed mat	8.2	7.7	6.6	83.3
	Sawdust+compost			6.4	80.9
Liberty	Weed mat	9.2	8.9	6.5	69.5
	Sawdust+compost			5.8	64.5
Significance [x]					
Year (Y)		*		NS	NS
Fertilizer Source (F)		NS		NS	NS
Mulch (M)		NS		*	*
Cultivar (C)		***		*	***
Exposure (E)		NS		NS	NS
Height (H)		NS		NS	NS
Y x C		NS		NS	*
C x E		NS		*	NS
Y x M x H		NS		**	*
F x M x E		*		NS	NS
F x C x E		NS		NS	*
F x C x H		NS		NS	*

[z] NS = non-significant; *,**,*** = significant at P ≤ 0.05, 0.01 and 0.001, respectively.
Non-significant two-way, three-way and four-way interactions not shown.
[y]Flowers per cluster counted on 5 May 2012 and 30 Apr. 2013.
[x]Berries per cluster counted on 9 June 2012 and 25 May 2013.

Table 3.6. Impact of cultivar on the number of flushes of growth and shoot length in certified organic northern highbush blueberry grown at the North Willamette Research and Extension Center, Aurora, OR in 2012-2013. (averaged over year, fertilizer source, mulch, exposure, and canopy height which were non-significant for the main effect).

	Flushes of growth (no.)		Shoot length (cm)	
Treatments [z]	East	West	East	West
Duke	2.5	2.8	9.1	11.8
Liberty	2.2	2.1	11.3	9.9
Significance [z]				
Year (Y)	NS		NS	
Fertilizer Source (F)	NS		NS	
Mulch (M)	NS		NS	
Cultivar (C)	NS		NS	
Exposure (E)	NS		NS	
F x E	NS		*	
C x E	*		**	
M x C x E	NS		**	

[z] NS = non-significant; *,**,*** = significant at $P \leq 0.05$, 0.01 and 0.001, respectively. Non-significant two-way, three-way and four-way interactions not shown.

Table 3.7. Impact of cultivar, fertilizer source, mulch, exposure, and canopy height on berry size during stage I, II, and III of development in certified organic northern highbush blueberry grown at the North Willamette Research and Extension Center, Aurora, OR in 2012-2013. Values are an average of diameter measured on each date within the stage (n= 6 per date). Analyzed as a split-split-plot design with year as the main effect, fertilizer source as the sub-plot effect and combinations of mulch, cultivar, exposure and canopy height as the sub-sub-plot effect.

Treatment [z]	Stage (I)[y]	Stage (II)[x]	Stage (III)[w]
Year (Y)	***	***	***
Fertilizer Source (F)	NS	NS	NS
Mulch (M)	*	NS	NS
Cultivar (C)	***	***	*
Exposure (E)	NS	NS	NS
Height (H)	*	NS	**
Y x C	NS	***	***
F x M	**	**	**
F x E	*	**	***
C x H	*	*	*
E x H	*	*	NS
M x C x E	*	NS	NS
M x C x H	NS	*	*
M x E x H	NS	*	NS
Y x M x E	*	NS	NS
F x C x H	NS	**	*

[z] NS = non-significant; *,**,*** = significant at $P \leq 0.05$, 0.01 and 0.001, respectively. Non-significant two-way, three-way and four-way interactions not shown.
[y]Stage I ranged from 25 Apr. to 4 June 2012 and 15 Apr. to 20 May 2013 for ‘Duke’ and from 25 Apr. to 14 June 2012 and 15 Apr. to 4 June 2013 for ‘Liberty’.
[x]Stage II ranged from 4–14 June 2012 and 20–30 May 2013 for ‘Duke’ and 14–29 June 2012 and 4–24 June 2013 for ‘Liberty’.
[w]Stage III ranged from 19 June to 9 July 2012 and 4–24 June 2013 for ‘Duke’ and 4–29 July 2012 and 29 June to 14 July 2013 for ‘Liberty’.

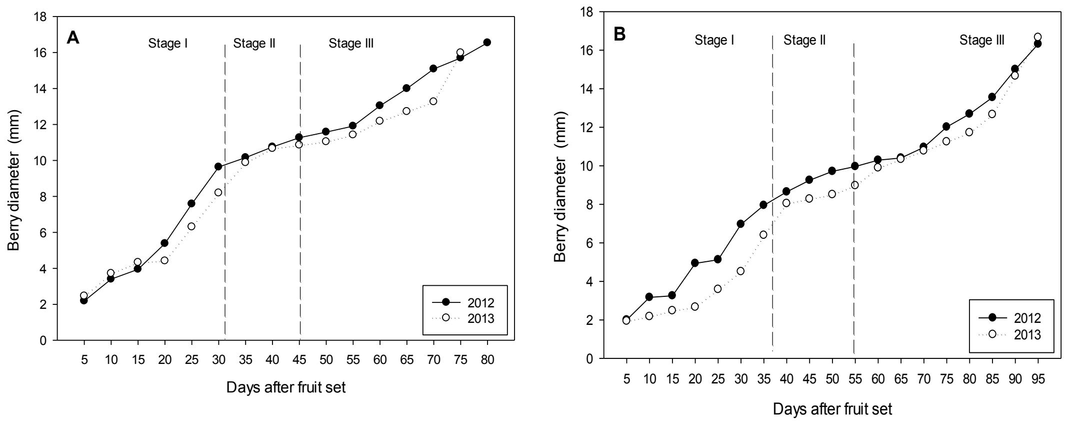

Fig. 3.1. Berry development of 'Duke' (**A**) and 'Liberty' (**B**) blueberry plants in 2012 and 2013. Each symbol represents the mean of 4 replicates averaged over fertilizer source, mulch, exposure, and canopy height for year.

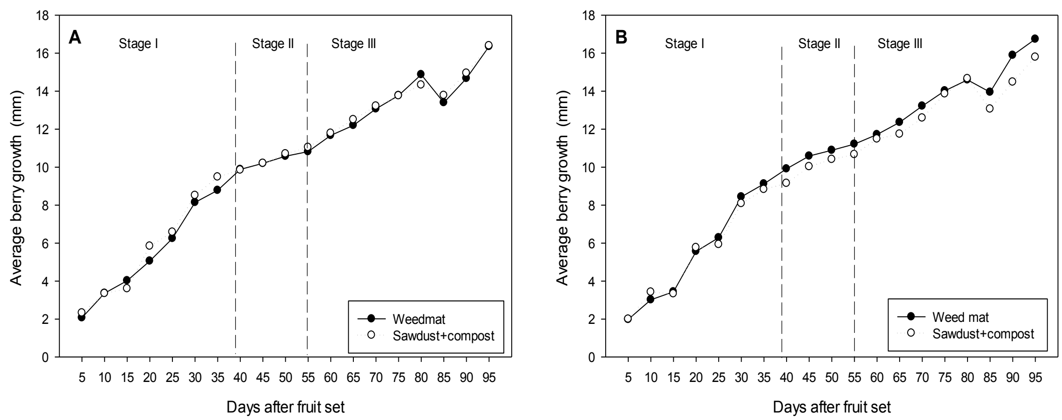

Fig. 3.2. Berry development of blueberry plants fertilized with fish emulsion (**A**) and feather meal (**B**) and mulched with weed mat or sawdust+compost, 2012. Each symbol represents the mean of 4 replicates averaged over year, cultivar, and canopy exposure and height.

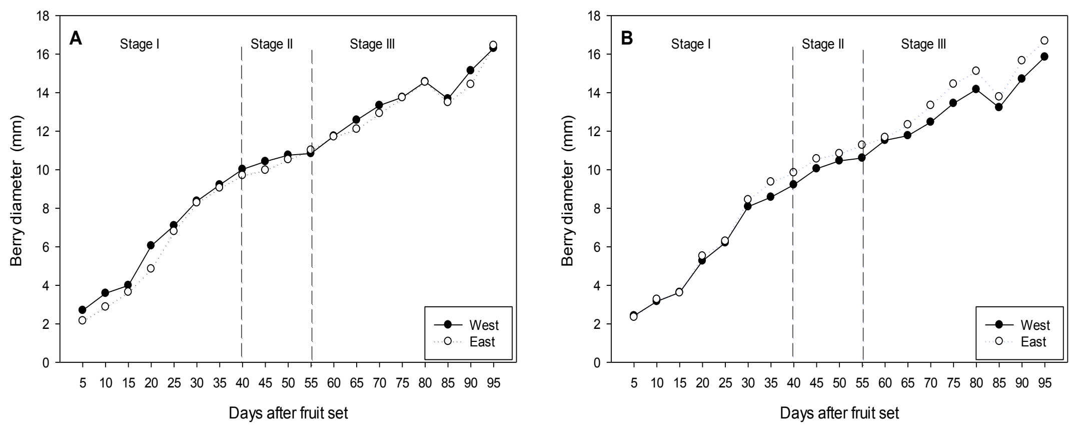

Fig. 3.3. Berry development of blueberry plants fertilized with fish emulsion (**A**) or feather meal (**B**) when located on the east or west side ("exposure") of the canopy, 2012. Each symbol represents the mean of 4 replicates averaged over cultivar, mulch and canopy height.

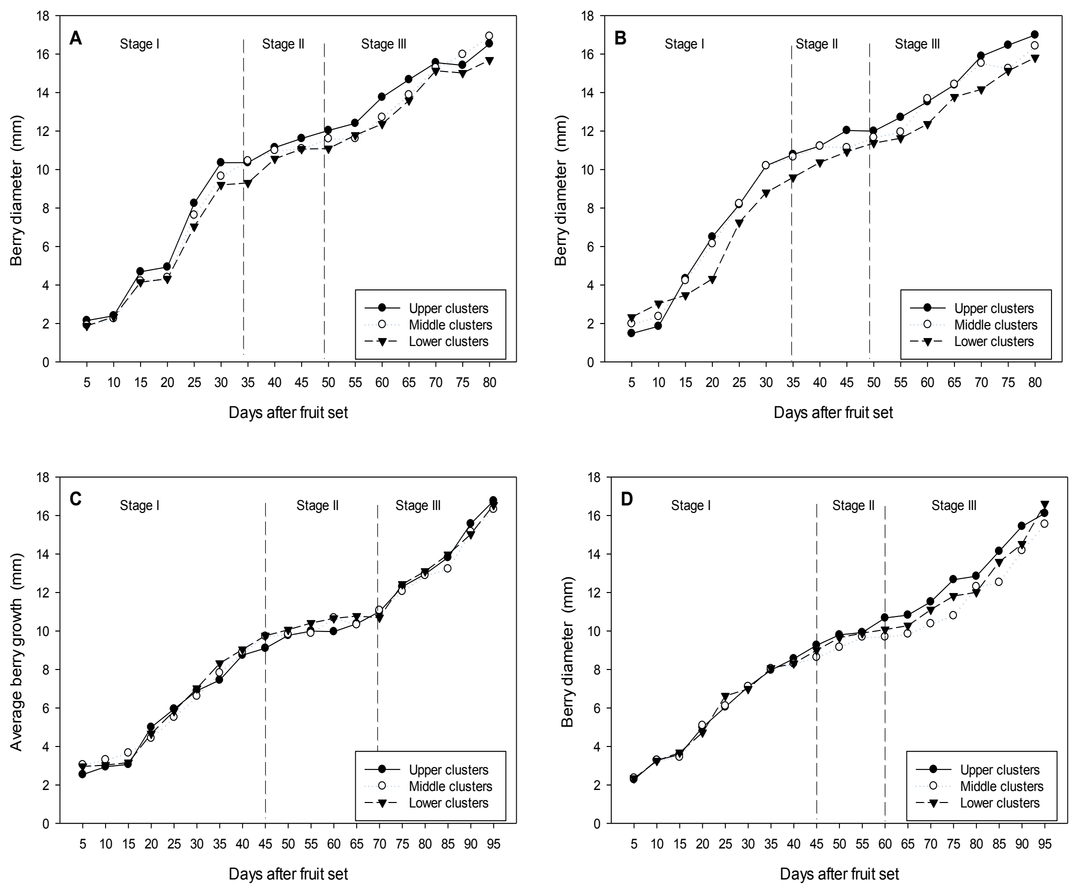

Fig. 3.4. Berry development in an organic planting of ‘Duke’ (**A**, **B**) and ‘Liberty’ (**C**, **D**) blueberry in 2012. Changes in berry diameter were measured at three canopy heights (upper, middle, and lower) in plants mulched with either weed mat (**A**, **C**) or sawdust+compost (**B**, **D**). Each symbol represents the mean of four replicates averaged over two fertilizer sources (fish emulsion and feather meal) and east and west canopy exposures.

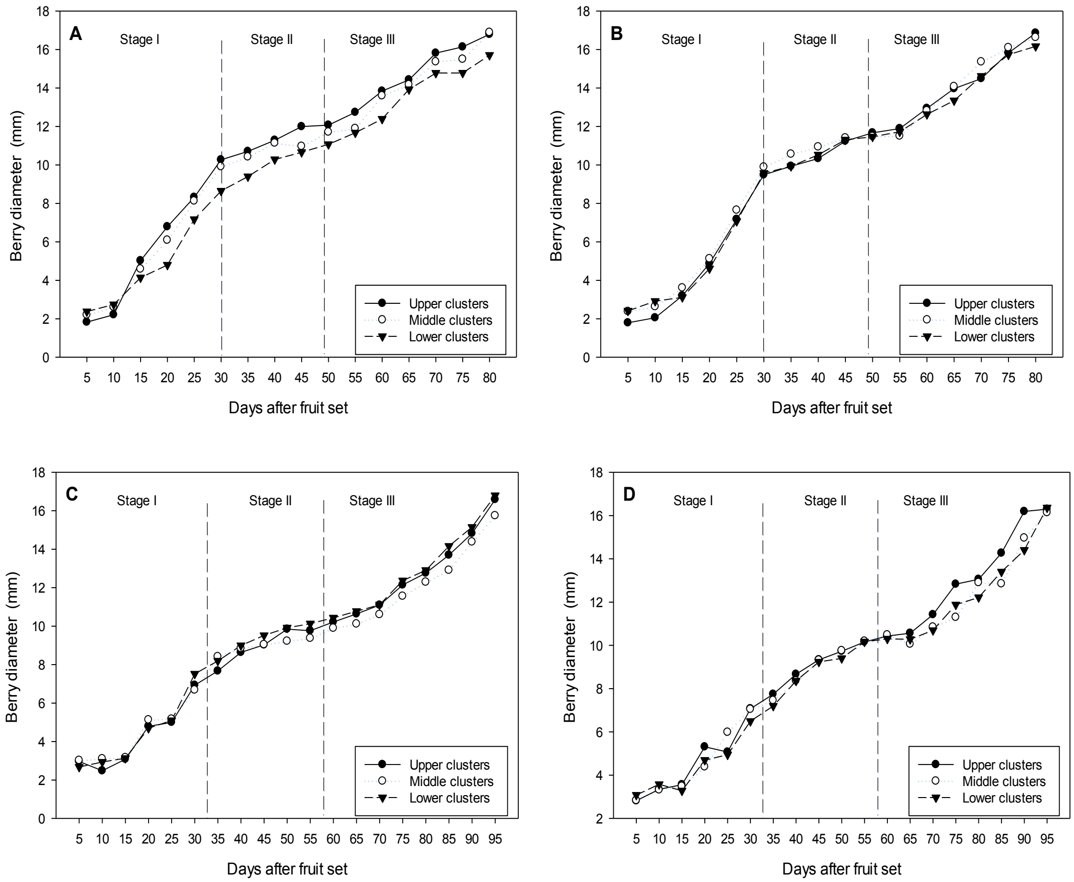

Fig. 3.5. Berry development in an organic planting of 'Duke' (**A**, **B**) and 'Liberty' (**C**, **D**) blueberry in 2012. Changes in berry diameter were measured at three canopy heights (upper, middle, and lower) in plants fertilized with fish emulsion (**A**, **C**) or feather meal (**B**, **D**). Each symbol represents the mean of four replicates averaged over two fertilizer sources (fish emulsion and feather meal) and east and west canopy exposures

Chapter 4 – Chemigation with Micronized Sulfur Rapidly Reduces Soil pH in a New Planting of Northern Highbush Blueberry

Khalid F. Alumtairi, Rui M.A. Machado, David R. Bryla, and Bernadine C. Strik.

Abstract.

Northern highbush blueberry (*Vaccinium corymbosum* L.) is adapted to low soil pH in the range of 4.5–5.5. When pH is higher, soil is usually acidified by incorporating elemental sulfur (S^o) prior to planting. A 2-year study was conducted to determine the potential of applying micronized elemental sulfur (S^o) by chemigation through the drip system to reduce high soil pH in a new planting of 'Duke' blueberry. The S^o was mixed with water and injected weekly for 2 months prior to planting, as well as 2 years after planting, at rates of 0, 50, 100 and 150 $kg \cdot ha^{-1}$ per year, and was compared to the conventional practice of incorporating prilled S^o into the soil prior to planting (two applications of 750 $kg \cdot ha^{-1}$ each). Chemigation quickly reduced soil pH (0-10 cm) within a month from 6.6 with no S^o to 6.1 with 50 $kg \cdot ha^{-1}$ S^o and 5.8 with 100 or 150 $kg \cdot ha^{-1}$ S^o. The change was short-term, however, and by May of the following year, soil pH averaged 6.7, 6.5, 6.2, and 6.1 with each increasing rate of S^o chemigation, respectively. The conventional treatment, in comparison, averaged 6.6 on the first date and 6.3 on the second date. In July the following year, soil pH ranged from an average of 6.4 with no S^o to 6.2 with 150 $kg \cdot ha^{-1}$ S^o and 5.5 with prilled S^o. Soil pH declined thereafter to as low as 5.9 with additional S^o chemigation and at lower depths (10–30 cm) was similar to the conventional treatment. None of the treatments had any effect on winter pruning weight in year 1 or on yield, berry weight, and plant dry weight in year 2. Leaf P, K, Ca, Mg, S, and Mn concentrations, on the other hand, were lower with S^o chemigation than with prilled S^o during the first year after planting, while leaf N, P, and S were lower with S^o chemigation during the second year. The findings indicate that S^o chemigation can be used to quickly reduce soil pH following planting and, therefore, may be a useful practice to correct high pH problems in established northern highbush blueberry fields. However, it was less effective and more time consuming than applying prilled S^o prior to planting.

Introduction

Northern highbush blueberry (*Vaccinium corymbosum* L.) is adapted to acidic soil conditions and is often most productive at a soil pH between 4.2 and 5.5 (Cain, 1952; Coville, 1910; Galletta, 1975; Korcak, 1988; Korcak et al., 1982; Hall et al., 1964; Harmer, 1944; Johnston, 1948; Townsend, 1966, 1967, 1969). In order to grow blueberry at sites with a higher initial soil pH, elemental sulfur (S^o), which oxidizes to sulfuric acid by chemotrophic soil bacteria such as *Thiobacillius* (Chapman, 1990; Deluca et al., 1989; Germida and Janzen, 1993; Lawrence and Germida, 1988; Lippman et al., 1916), is often mixed into soil prior to planting (Bailey, 1978; Ballinger, 1966; Camberato, 1999; Chandler et al., 1985). In many soils, large amounts of S^o (> 1500 $kg \cdot ha^{-1}$) are needed for the process (Cifuentes and Lindermann, 1993; Deluca et al., 1989; Horneck et al., 2004; Konopka et al., 1986; Modaihsh et al., 1989; Roig et al., 2004), and in some cases, such as in soils with high amounts of calcium carbonate, S^o acidification is unfeasible (Lindermann et al., 1991; Modaihsh et al., 1989; McCready and Krouse 1982; Neilsen et al., 1993; Slaton, 1998). Soil incorporation of S^o is also limited after planting because blueberry has a shallow root system (< 0.3 m deep; Bryla and Strik, 2007). Therefore, when soil pH is too high after planting, growers must either apply S^o on the soil surface or inject acid (e.g., sulfuric acid) into the irrigation water (chemigation). However, surface application of S^o is ineffective in dry environments and difficult to do in fields mulched with geotextile fabric (weed mat), and acid chemigation is hazardous and requires expensive, non-corrosive irrigation equipment (Retamales and Hancock, 2012).

Soil acidification with S^o usually takes several months or more to change soil pH from 6.0 or higher to a desired level for northern highbush blueberry (Gough, 1994; Hart et al., 2003, 2006; Retamales and Hancock, 2012). The rate is largely dependent upon soil temperature (Jaggi et al., 2005; Loser et al., 2001; Tyagi et al., 1996; Watkinson and Lee, 1994), moisture (Jaggi et al., 2005; Konopka et al., 1986; Nor and Tabatabai, 1977), and organic matter content (Cifuentes and Lindermann, 1993; Wainwright et al, 1986), as well as size of the S^o particles (Boswell and Friesen, 1993; Boswell et al., 1996; Fox et al., 1964; Hu et al., 2002; Lee et al., 1988; Germida and Janzen, 1993; Lefroy and Blair, 1997; Sholeh and Blair, 1997; Zhao et al., 2015; 2016). Generally, smaller S^o particles are oxidized more quickly than larger particles due to the greater surface area (Janzen et al., 1982: Janzen and Bettany, 1986; Koehler and Roberts, 1983; Laishley et al., 1984, Lawrence and Germida, 1988; Li and Caldwell, 1966; Tichy et al., 1998).

The objective of this study was to determine the potential of applying micronized S^o by chemigation through the drip system to quickly reduce soil pH in a new planting of northern highbush blueberry. Currently, there are several micronized S^o products on the market labelled for chemigation. We hypothesized that S^o chemigation would 1) reduce soil pH faster than conventional applications of prilled S^o and 2) require less product because the S^o is concentrated beneath the drip emitter where the root system is concentrated (Bryla et al., 2016) and soil conditions are moist and favorable for rapid bacterial transformation to sulfuric acid. The micronized S^o was applied before planting to evaluate its use as a pre-plant amendment and after planting to assess its value for reducing soil pH once a field is established.

Material and Methods

Study site. The study was conducted at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, OR in a field of highbush blueberry (cv. 'Duke') planted on 21 Oct. 2010. Soil at the site is a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerolls). The soil had an initial pH of 6.6 prior to any treatment and contained 2.4% organic matter. Plants were obtained from a commercial nursery as 2-year-old container stock and spaced 0.76 x 3.05 m apart on raised beds (0.4-m high and 0.9-m wide). The beds were shaped 3 months to planting in order to initiate the So treatments (see below). A 5-cm-deep layer of douglas fir (*Pseudotsuga menziesii* Franco) sawdust was rototilled ≈20-cm deep into each row just prior to making the beds using, a bed shaper (Kennco Manufacturing, Inc., Ruskin, FL). A 5-cm-deep layer of sawdust mulch was also applied on top of the beds after planting and reapplied in May 2012.

Sulfur treatments. Micronized wettable S^o (0–0–0–80S; Nufarm Americas Inc., Burr Ridge, IL) was mixed with water (0–6.8 $g \cdot L^{-1}$) and applied once or twice weekly by chemigation at a rate of 0, 50, 100, and 150 $kg \cdot ha^{-1}$ S per year, for 2 months prior to planting (28 July–27 Sept. 2010) and during the second year after planting (3 Aug.–12 Oct. 2012), and compared to the conventional practice of incorporating a prilled S^o (0–0–0–90S; Tiger-Sul Products LLC, Atmore, AL) into the soil prior to planting. Prilled S^o was applied in two applications of 750 $kg \cdot ha^{-1}$ each on 28 July and 10 Oct. 2010; the first application was rototilled into the plots along with the sawdust mulch, and the second was incorporated using a hand rake.

The treatments were arranged in a randomized complete block design with five plots of four plants each per treatment. Drip tubing (Netafim USA, Fresno, CA) was installed on each side of the row at a distance of 15 cm from the base of the plants. The tubing had 2 $L \cdot h^{-1}$ in-line emitters every 0.3 m and was installed immediately after the beds were shaped. The wettable S^o solution was injected through the drip system using water-powered proportional chemical injector (Model D25F1; Dosatron, Clearwater, FL) installed in a manifold located at the head of each treatment. Irrigation was initiated ≈10 min prior each injection to fully pressurize the system and run for at least 10 min after injection to flush the lines. A water only control was applied at the same rate to treatments with no S^o injection.

Crop management. Weeds were mowed between rows, as needed, and removed by hand at least once a month from the planting beds. Irrigation was scheduled as needed to meet crop water demands over each growing season (Bryla et al., 2011). Plants were fertilized with granular ammonium sulfate (20N–0P–0K) and liquid urea (20N–0P–0K). The ammonium sulfate was applied by hand around the base of the plants at rate of 10 kg·ha^{-1} N each on 27 Apr. and 11 May 2011, and the liquid urea was injected weekly through the drip system at a rate of 8 kg·ha^{-1} N per application from 25 May to 27 July 2011 and 15 June to 27 July 2012. No chemicals were used for pest control.

Measurements. Plant growth occurred primarily from May to October each year. Plants were pruned after planting in Oct. 2010 and on 18 Feb. in 2012. To encourage growth, flower buds were totally removed from the plants during the first pruning and limited to 40–80 per plant prior to the following season (Strik and Buller, 2005). All prunings were weighed fresh from each plot during the second pruning.

Soil samples were collected in each plot using a 2-cm-diameter soil probe (Clements Associates Inc., Newton, IA). The soil was cored 3 cm from a drip emitter, to a depth of 10 cm, on 18 Aug. 2010 (prior to planting) and 18 May 2011 (beginning of first growing season); and was cored under a drip emitter and at 5, 10, and 15 cm on each side of the emitter (perpendicular to row), to a depth of 0-10, 10-20, and 20-30 cm at each location, on 18 July and 11 Oct. 2011 and 23 July and 21 Oct. 2012. Each sample was taken near a different emitter in each plot on each date. The collected samples were oven-dried at 48 ^{o}C, ground to pass through a 2-mm sieve, mixed with two parts water (w/w), and analyzed for pH using a calibrated pH/ion meter (model S220 SevenCompact, Mettler-Toledo, LCC, Columbus, OH) and for salinity using a calibrated conductivity meter (Omega Engineering, Inc., Stamford, CT).

Five leaves per plot were collected for nutrient analysis on 3 Aug. 2011 and 10 Aug. 2012. The leaf samples were oven-dried for 3 d at 40 °C, ground to pass through a 40-mesh screen (0.42-mm openings), and analyzed for N using a combustion analyzer (CN-2000; Leco Inc., St. Louis, Mo.) and analyzed for P, K, Ca, Mg, S, Fe, B, Cu, Mn, and Zn using ICP-OES (Optima 3000DV; Perkin Elmer, Wellesley, Mass.) after wet ashing in nitric acid (Gavlak et al., 1994).

Ripe fruit were handpicked and weighed from each plot on 9 July, 18 July, and 3 Aug. 2012. A random sample of 100 berries/plot was also weighed on each date and used to calculate the weighted average berry weight.

One representative plant per plot was harvested destructively on 14 Dec. 2012. The plants were excavated with a shovel and washed with a hose to remove soil from the roots. Each plant was then separated into whips, new branches, woody canes (1- and 2-year-old wood), and roots (including the crown), oven-dried for 3 weeks at 70 ^{o}C, and weighed.

Statistical analysis. Data were analyzed by analysis of variance using the PROC MIXED procedure in SAS v. 9.1 (SAS Institute, Inc., Cary, NC).

Results and Discussion

Soil pH. Chemigation quickly reduced soil pH (0–10 cm) within a month of the first application of S^o from an average of 6.6 with no S^o to 5.8 with 100–150 $kg \cdot ha^{-1}$ S^o (Fig. 4.1; Aug. 2010). However, the change in pH was short-term and by May of the following year ranged from 6.7 with no S^o to 6.1 with 150 $kg \cdot ha^{-1}$ of S^o applied. Prilled S^o, in contrast, reduced soil pH gradually and only to 6.3 by May (Fig. 4.1). Despite plenty of precipitation prior to May, soil acidification was likely inhibited by the large size of the prilled S^o granules and by low soil temperatures during the first few months after planting (Fig. 4.2). The optimum temperature for S^o acidification by most *Thiobacillus* sp. is between 15 and 25 ^{o}C (Freney, 1967; Nor and Tabatabai, 1977; Watkinson and Lee, 1994).

By the time soil temperature exceeded 15 ^{o}C in July 2011, soil pH averaged 5.6 in the top 10 cm of the soil profile with prilled S^o (Fig. 4.3A). The chemigation treatments, on the other hand, appeared to be dominated by hydrolysis of the urea fertilizer, which increases soil pH (Broadbent et al., 1958). Without S^o, soil pH was

6.7 under the drip emitter and declined with distance and depth from the emitter. Soil pH was only < 6.0 at the highest rate of S^o applied through chemigation and, in this case, only near the drip emitter. By Oct. 2011, soil pH was only slightly lower with than without S^o chemigation and generally decreased with soil depth along the drip line (Fig. 4.3B). Soil pH was also greater in October than in July in the conventional treatment but still lower, on average, than with S^o chemigation at 0–10 cm. Nearly 55 mm of rain fell during the week prior to soil sampling in Oct. 2011, which probably leached H^+ and diluted the pH of the soil.

Soil pH continued to decline in 2012 in each treatment, including the control with no S^o (Fig. 4.4). A drop in pH is common in northern highbush blueberry fields and is due primarily to nitrification of excess ammonium-N from the fertilizer (Bryla et al., 2010). Blueberry requires primarily the ammonium form of N and, therefore, is usually fertilized with ammonium sulfate or urea. Young plants require < 20 $kg \cdot ha^{-1}$ N during the first year after planting (Bañados et al., 2012), and therefore, at least 80 $kg \cdot ha^{-1}$ N would have likely nitrified into nitrate-N in year 1 of the present study. In July 2012, soil pH averaged 6.2–6.4 at 0–10 cm with increasing rates of S^o chemigation and 5.5 with prilled S^o (Fig. 4.4A). In general, soil pH declined with horizontal distance from the drip emitter and increased with depth in all but the no S^o treatment.

As with the pre-plant application of S^o, chemigation also reduced soil pH quickly after planting (Fig. 4.4B). Even with 67 mm of rain prior to sampling, soil pH in Oct. 2012 was 5.9–6.1 in the top 10 cm when the soil was chemigated with an additional 100–150 kg ha^{-1} S^o, and at the highest chemigation rate, was similar to the prilled S^o treatment, on average, at both the 10–20 and 20–30 cm depths. Thus, chemigation with S^o rapidly reduced soil pH both prior to and after planting in the present study, and when applied after planting, resulted in deep soil acidification.

Soil EC. A potential side-effect of S^o acidification is high levels of salinity in the soil. Acidification with S^o increases soil salinity by releasing sulfate (SO_4^{2-}) and other soluble ions (e.g., PO_4^{2-}, Mn^{2+} and Zn^{2+}) (Jaggi et al., 2005; Spiers, 1984; Spiers and Braswell, 1992; Yang et al., 2010; Zhou et al., 2002). Indeed, soil salinity, which is measured as EC, increased with S^o application in the present study and, consequently, was negatively correlated to soil pH on each sampling date (r^2 = 0.94-0.99; $P \leq 0.01$). In general, soil EC was lower with S^o chemigation than with conventional S^o, but the readings never exceeded 0.6 $dS \cdot m^{-1}$ in either treatment on any of the sampling dates (data not shown). Soil EC < 2.0 $dS \cdot m^{-1}$ is considered safe for salt-sensitive crops such as northern highbush blueberry (Grieve et al., 2012). Thus, it is unlikely that any of the treatments were affected by salinity in the present study.

Plant growth, production, and leaf nutrients. The S^o treatments had no effect on pruning weight, yield, berry weight, or plant dry weight during first 2 years after planting (Table 4.1). In general, growth and production were normal for ‘Duke’ in Oregon (Strik and Buller, 2005). Leaf P, K, Ca, Mg, S, and Mn concentrations, on the other hand, were lower with S^o chemigation than with prilled S^o in year 1, while leaf N, P, and S were lower with S^o chemigation in year 2 (Table 4.2). The concentration of each nutrient was within or above the normal range for northern highbush blueberry in Oregon the first year (Hart et al., 2006). However, leaf P was below optimum (< 0.1%) the following year, and leaf N was deficient (< 1.5%). Nitrogen fertilization was late and lower than recommended the second year (Bryla and Strik, 2015). Consequently, the plants were slightly chlorotic that spring but recovered quickly once chemigation was initiated and one or two applications of urea were applied.

It is unclear why growth was unaffected by any of the treatments, including no S^o, given that soil pH at the site was quite high for northern highbush blueberry. Duke often performs poorly and usually worse most other cultivars when soil pH is too high (Strik et al., 2014). However, none of the plants in the study exhibited interveinal Fe chlorosis commonly associated with high soil pH in northern highbush blueberry (Caruso and Ramsdell, 1995). This suggests that bulk soil pH measurements may be less important when the plants are irrigated and fertigated by drip. As mentioned, blueberry roots tend to concentrate near the drip emitters and, therefore, may be more affected by pH of the rhizosphere than of the soil. More work is needed to understand pH dynamics of drip-irrigated plants.

Conclusions

The findings indicate that S^o chemigation can be used to quickly reduce soil pH in northern highbush blueberry. However, it was less effective and more time consuming than conventional application of prilled S^o prior to planting. Therefore, S^o chemigation may be most useful when soil pH is too high after planting. The practice is less expensive and safer than using acid to correct high soil pH problems and is a convenient alternative for both conventional and organic blueberry production.

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Tables and Figures

Table 4.1. Effects of soil acidification by chemigation and conventional applications with elemental sulfur (S^o) on growth and early fruit production during the first 2 years after planting in 'Duke' blueberry.

Method and rate	Pruning wt	Yield	Berry wt	Plant dry wt (kg/plant)[x]	
S^o application	(g/plant)[z]	(kg/plant)[y]	(g)[y]	Shoot	Roots
Chemigation					
0 $kg \cdot ha^{-1}$ S^o	40	3.1	2.62	0.24	0.32
50 $kg \cdot ha^{-1}$ S^o	35	3.5	2.59	0.23	0.30
100 $kg \cdot ha^{-1}$ S^o	38	3.1	2.62	0.21	0.29
150 $kg \cdot ha^{-1}$ S^o	35	2.6	2.63	0.23	0.30
Conventional	33	2.6	2.73	0.25	0.33
Significance	NS	NS	NS	NS	NS

[z]Measured following the first growing season.

[y]Measured during the second growing season.

[x]Measured following the second growing season. The shoot includes the whips, new branches, and woody canes, and roots include the crown.

NS – nonsignificant.

Table 4.2. Effects of soil acidification by chemigation and conventional applications with elemental sulfur (S^o) on leaf nutrient concentrations during the first 2 years after planting in 'Duke' blueberry.

Method and rate	Leaf macronutrients ($mg \cdot g^{-1}$)						Leaf micronutrients ($\mu g \cdot g^{-1}$)				
of S^o application	N	P	K	Ca	Mg	S	Fe	B	Cu	Mn	Zn
Year 1											
Fertigation											
0 $kg \cdot ha^{-1}$ S^o	2.07	0.11 b[z]	0.60 b	0.66 b	0.24 b	0.52 b	189	34	3	371 b	21
50 $kg \cdot ha^{-1}$ S^o	1.95	0.10 b	0.60 b	0.67 b	0.25 b	0.51 b	191	33	3	381 b	20
100 $kg \cdot ha^{-1}$ S^o	2.00	0.10 b	0.64 b	0.68 b	0.27 b	0.55 b	188	34	3	373 b	20
150 $kg \cdot ha^{-1}$ S^o	1.95	0.11 b	0.61 b	0.70 ab	0.27 b	0.55 b	197	36	2	393 b	24
Conventional	1.94	0.13 a	0.89 a	0.83 a	0.38 a	1.00 a	188	40	3	570 a	24
Significance	NS	**	**	**	**	**	NS	NS	NS	**	NS
Year 2											
Fertigation											
0 $kg \cdot ha^{-1}$ S^o	1.19 b	0.07 b	0.50	0.56	0.19	0.10 b	410	49	6	178	12 a
50 $kg \cdot ha^{-1}$ S^o	1.23 b	0.07 b	0.52	0.55	0.19	0.11 b	414	51	7	146	11 ab
100 $kg \cdot ha^{-1}$ S^o	1.24 b	0.07 b	0.50	0.51	0.18	0.10 b	475	48	6	154	11 ab
150 $kg \cdot ha^{-1}$ S^o	1.22 b	0.07 b	0.51	0.55	0.19	0.10 b	368	54	6	157	11 ab
Conventional	1.38 a	0.08 a	0.50	0.54	0.19	0.16 a	428	55	5	185	10 b
Significance	**	*	NS	NS	NS	**	NS	NS	NS	NS	*

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

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

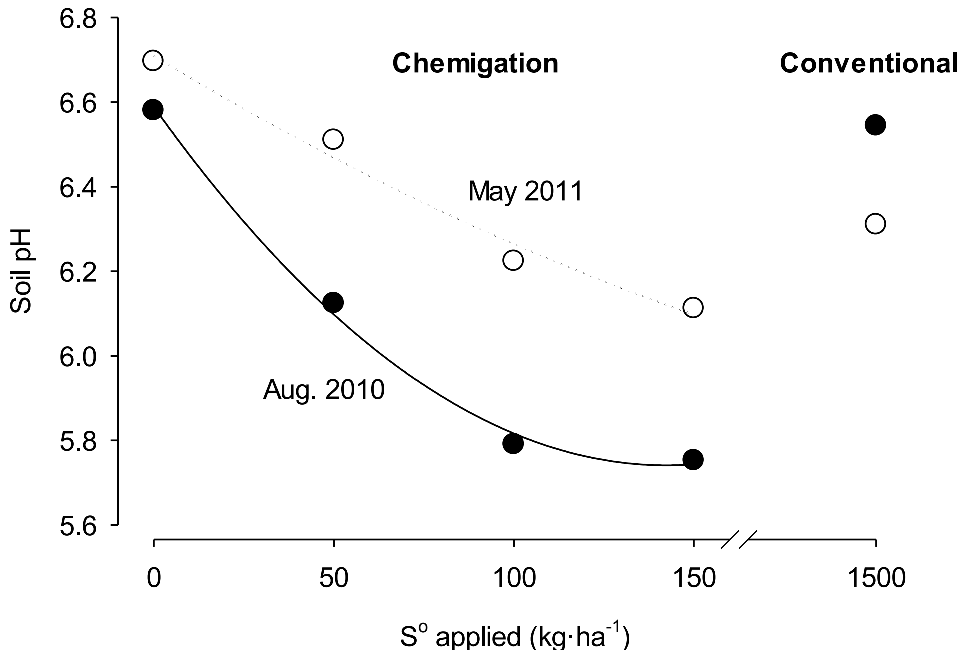

Fig. 4.1. Soil pH during (Aug. 2010) and 7 months following (May 2011) chemigation and conventional applications with elemental sulfur (S^o) in a new planting of ‘Duke’ blueberry. Soil was sampled near a drip emitter at a depth of 0–10 cm.

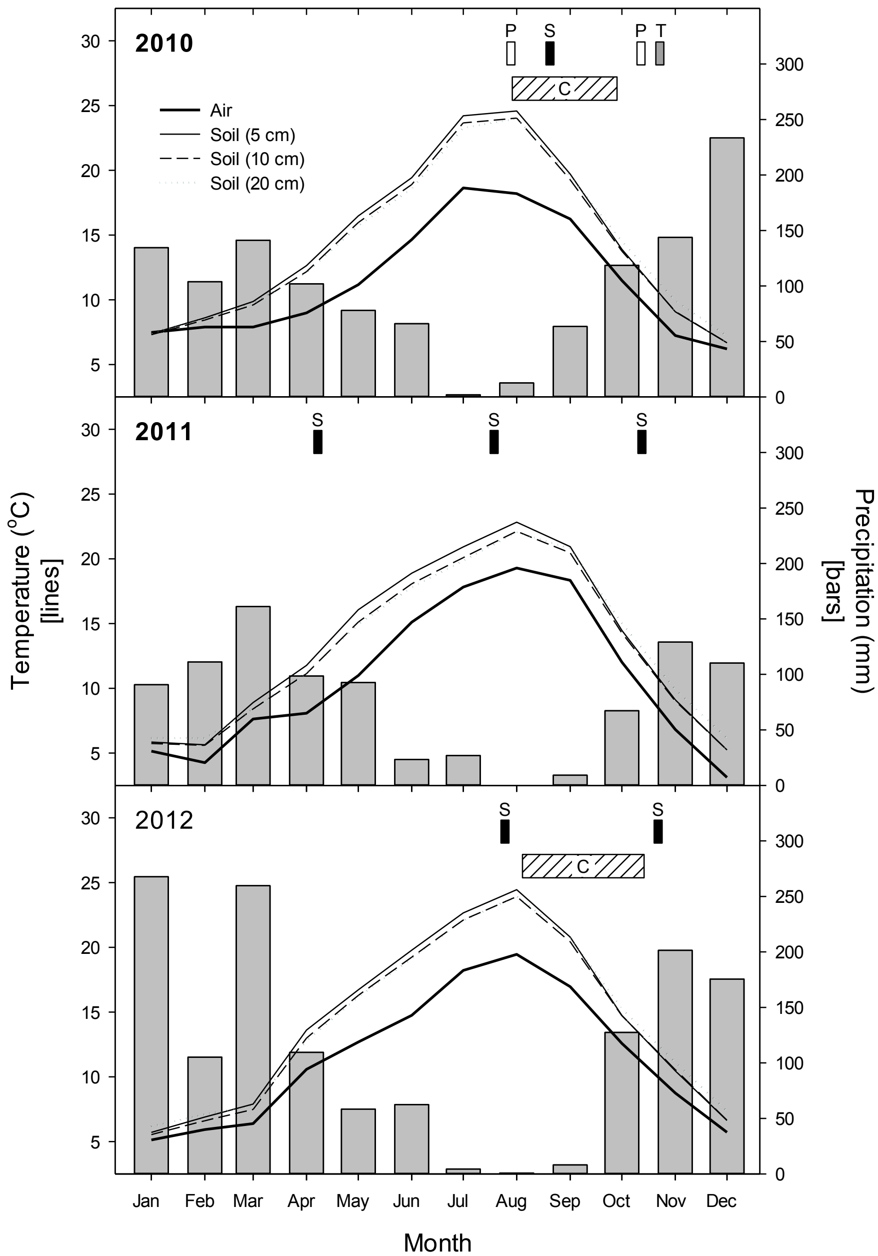

Fig. 4.2. Temperature and precipitation in a new field of 'Duke' blueberry that was either chemigated or treated conventionally with elemental sulfur (S^o). Hashed bars with 'C' indicates the dates in which S^o was applied by chemigation; white bars with 'P' indicates the dates in which prilled S^o was applied conventionally; the gray bar with a 'T' represents the date in which the plants were transplanted; and black bars with an 'S' represent the dates in which soil was sampled and analyzed for pH and electrical conductivity.

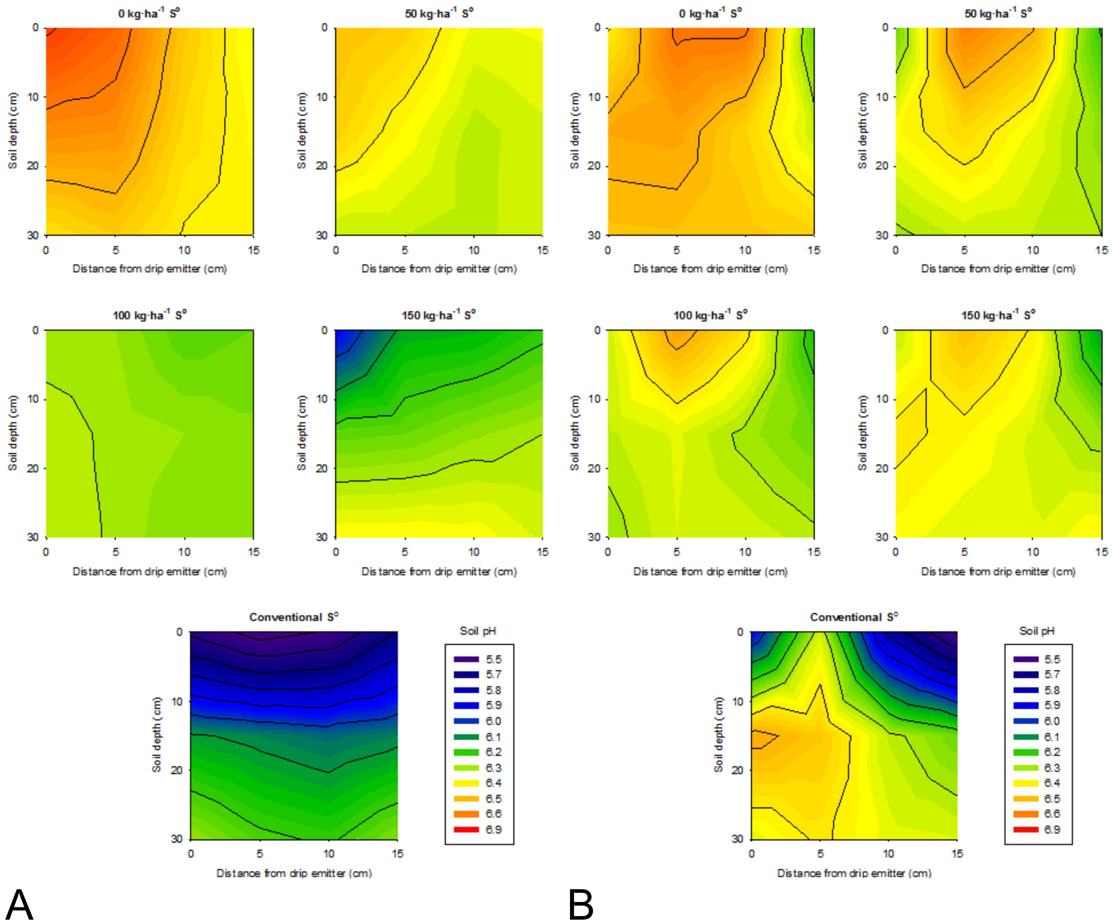

Fig. 4.3. Soil pH in relation to soil depth and distance from a drip emitter following chemigation and conventional applications with elemental sulfur (S°) in a new planting of 'Duke' blueberry. Measurements were taken in (**A**) July and (**B**) Oct. 2011 during the first year after planting.

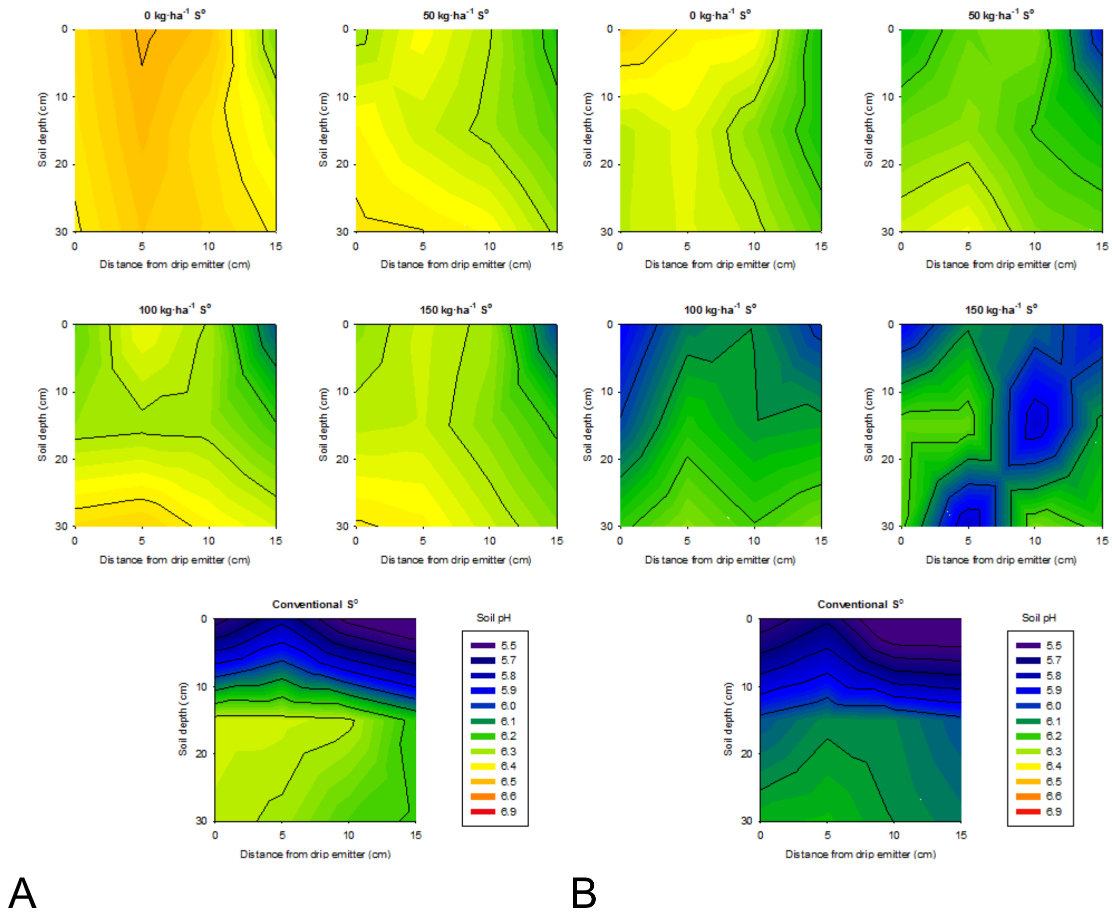

Fig. 4.4. Soil pH in relation to soil depth and distance from a drip emitter following chemigation and conventional applications with elemental sulfur (S°) in a new planting of 'Duke' blueberry. Measurements were taken in (**A**) July and (**B**) Oct. 2012 during the second year after planting.

Chapter 5 – General Conclusions

Khalid F. Almutairi

The results of this work revealed two possible options for reducing irrigation water use in northern highbush blueberry, including deficit irrigation and early irrigation cut-offs. 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 second year when the plants were unthinned and produced smaller berries with less soluble solids content than either full or deficit irrigation. Therefore, judicious use of early cut-off irrigation may be warranted during years with severe water restrictions.

Cutting off irrigation late also reduced water use but produced considerably less yield than the other treatments. On average, this 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 cut-offs 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 cut-off early in order 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 over-thinning through more severe pruning is an effective tool for mitigating drought and water restrictions.

Furthermore, the proportion of fruit buds was affected by the location of the lateral in the canopy (height and exposure). Laterals in the upper canopy tended to be more vigorous and had a greater diameter than those in the mid- and lower canopy. In general, fruit development within clusters was more uniform in the early season cultivar, ‘Duke’, than in a mid-late-season cultivar, ‘Liberty’. This resulted in relatively uniform fruit size among harvests in ‘Duke’ as compared to ‘Liberty’. The smaller berries, located in lower clusters and picked during the last harvest of ‘Liberty’ took longer to mature than in ‘Duke’. These results suggest that pruning proportionally more on the lower part of the canopy, while keeping the canopy open, will result in larger fruit at harvest than uniform pruning throughout the bush, whereas less pruning on the upper canopy will shade the lower parts and delay the harvest with smaller fruits.

Finally, S^o chemigation can be used to quickly reduce soil pH in northern highbush blueberry. However, it was less effective and more time consuming than conventional application of prilled S^o prior to planting. Therefore, S^o chemigation may be most useful when soil pH is too high after planting. The practice is less expensive and safer than using acid to correct high soil pH problems and is a convenient alternative for both conventional and organic blueberry production.

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