AN ABSTRACT OF THE DISSERTATION OF

Oscar L. Vargas for the degree of Doctor of Philosophy in Horticulture presented on April 2, 2015.
Title: Nitrogen Fertigation Practices to Optimize Growth and Yield of Northern Highbush Blueberry (*Vaccinium corymbosum* L.)

Abstract approved:

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David R. Bryla

Northern highbush blueberry is a long-lived perennial crop that is well adapted to low soil pH conditions. The plants are often shallow rooted and absorb primarily the ammonium (NH_4) form of nitrogen (N) rather than nitrate-N (NO_3-N). Traditionally, commercial blueberry fields have been irrigated with overhead sprinklers and fertilized using granular sources of NH_4-N. However, many new plantings of blueberry are irrigated by drip and fertigated by injecting liquid sources of N directly through the drip system. Three studies were conducted in western Oregon to compare fertigation to granular fertilizers and to develop methods to enhance the potential benefits of the practice. The first study was conducted in an established planting of 'Bluecrop' blueberry during the first 5 years of fruit production (year 3–7). Liquid sources of ammonium sulfate or urea were injected through a drip system in equal weekly applications from mid-April to early August. Granular sources of the fertilizers were applied on each side of plants, in three split applications from mid-April to mid-

June, and washed into the soil using microsprinklers. Each fertilizer was applied at three N rates, which were increased as the plants matured (63 to 93, 133 to 187, and 200 to 280 kg·ha^{-1} N) and compared with non-fertilized treatments (0 kg·ha^{-1} N). Yield was 12% to 40% greater with fertigation than with granular fertilizer each year as well as with ammonium sulfate than with urea during the fourth year. Leaf N concentrations were also greater with fertigation in 4 of 5 years and greater with ammonium sulfate than with urea each year. The plants produced fewer roots with fertigation than with granular fertilizer, but the median lifespan of the roots was 60 days longer with fertigation. Soil pH declined with increasing N rates and was lower with granular fertilizer than with fertigation the first 3 years and was lower with ammonium sulfate than with urea in all but one year. Total yield averaged 32 to 63 t·ha^{-1} in each treatment over the first 5 years of fruit production and was greatest when plants were fertigated with ammonium sulfate or urea at rates of at least 63 to 93 kg·ha^{-1} N per year. The second study was conducted to evaluate the use of conventional drip and alternative micro irrigation systems in six newly planted cultivars (‘Earliblue’, ‘Duke’, ‘Draper’, ‘Bluecrop’, ‘Elliott’, and ‘Aurora’) of northern highbush blueberry. The drip system included two lines of tubing on each side of the row with in-line drip emitters at every 0.45 m. The alternative systems included geotextile tape and microsprinklers. The geotextile tape was placed alongside the plants and dispersed water and nutrients over the entire length. Microsprinklers were installed between every other plant at a height of 1.2 m. Nitrogen was applied by fertigation at annual rates of 100 and 200 kg·ha^{-1} N by drip, 200 kg·ha^{-1} N by geotextile tape, and 280 kg·ha^{-1} N by microsprinklers. By the end of the first season, plant size, in terms of canopy cover, was greatest with geotextile tape, on average, and lowest with microsprinklers or drip at the lower N rate. The following year, canopy cover was similar with geotextile tape and drip at the higher N rate in each cultivar, and was lowest with microsprinklers in all but 'Draper'. In most of the cultivars, geotextile tape and drip at the higher N rate resulted in greater leaf N concentrations than microsprinklers or drip at the lower N rate, particularly during the first year after planting. By the third year, yield averaged 3.1 to 9.1 t·ha^{-1} among the cultivars, but was similar with geotextile tape and drip at either N rate, and was only lower with microsprinklers. Overall, drip was more cost effective than geotextile tape, and fertigation with 100 kg·ha^{-1} N by drip was sufficient to maximize early fruit production in each cultivar. Microsprinklers were less effective by comparison and resulted in white salt deposits on the fruit. The final study was conducted in a new planting of 'Draper' blueberry to identify methods to increase the efficiency of fertigation with N fertilizer. Previous research indicated that more N was needed by fertigation during first year or two after planting because, unlike granular fertilizer, which could be applied by hand around the base of the plants, at least half of the N injected through the drip system was applied between the plants and beyond the root system. Twelve treatments were included in the present study, including four with different drip configurations, six with alternative fertilizers, and two to determine whether pre-plant or late-season applications of N fertilizer was beneficial with fertigation in blueberry. After 2 years, total plant dry weight was 28% to 58% greater with one or two drip lines near the base (crown) of the plants than with two lines located at 20 cm on each side of the row, even when granular or slow-release fertilizer was applied in early spring prior to fertigation with the wider drip lines. Wider drip lines often resulted in lower leaf N concentrations than other treatments and increased salinity (electrical conductivity) in the root zone. The use of alternative fertilizers such as urea sulfuric acid was effective at reducing soil pH but resulted in the same plant dry weight as liquid urea, while humic acids with N and other nutrients increased root dry weight by an average of 60% relative to any other treatment, including a control that contained the same nutrients. Pre-plant and extended N application had no measureable effect on plant growth. Overall, the results of these studies indicate that fertigation was generally more beneficial than granular applications of N fertilizer and, in new plantings, was most effective when drip lines were located near the base of the plants. Humic acids were also useful for increasing root production during establishment.

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Nitrogen Fertigation Practices to Optimize Growth and Yield of Northern Highbush Blueberry (*Vaccinium corymbosum* L.)

by

Oscar L. Vargas

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APPROVED:

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Head of the Department of Horticulture

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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.

Oscar L. Vargas, Author

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CONTRIBUTION OF AUTHORS

Dr. David Bryla was involved in the experimental design, statistical interpretation, and writing of all the chapters of this document. Dr. Bernadine Strik assisted with data interpretation on chapters four and five. Dr. Dan Sullivan and Dr. Patrick Brown assisted with data interpretation of chapter five. Dr. Luis Valenzuela-Estrada assisted with experimental design and data interpretation of chapter 3. Dr. Jerry Weiland assisted with plant disease diagnosis and data interpretation of chapter 4. Dr. Luna Sun assisted with statistical model design of all chapters in this dissertation. Mr. Josh Kubischta assisted with field work on each project and was responsible for the majority of the root image analysis in chapter 3.

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DEDICATION

This dissertation is dedicated to my mother, to my sister, Mimi, and to my brothers, Jorge and Félix.

NITROGEN FERTIGATION PRACTICES TO OPTIMIZE GROWTH AND YIELD

OF NORTHERN HIGHBUSH BLUEBERRY (*Vaccinium corymbosum* L.)

Chapter 1 – General Introduction

Oscar L. Vargas

Northern highbush blueberry (*Vaccinium corimbosum* L.) has become a major crop worldwide and is currently grown on six continents. The strong demand for fresh fruit and a developing processed industry have given good returns to growers, resulting in continued increase of the planted area in most growing regions. During the past seven years, the worldwide planted area has increased at a rate of ≈10% per year with 58,400 ha in 2007 and 110,900 ha in 2014. The total fruit produced in 2014 was 560,000 metric tons and is estimated to increase to 770,000 metric tons by 2019. In 2014, the worldwide top four countries for planted area of highbush blueberry were the United States, Chile, Canada, and China, accounting for ≈65% of the total. In 2014, Oregon reached 4,100 ha of blueberry representing 17% of the planted area in the Pacific Northwest, and a farm gate value of around $100 million (Strik, 2007; Brazelton, 2014).

Northern highbush blueberry is a long-lived perennial crop with a long fruiting life and normally reaches full production by the seventh year after planting. Blueberry is well adapted to acidic soil conditions and often grows best in a pH range of 4.0 to 5.5 (Retamales and Hancock, 2012). Plants respond positively to organic matter additions and benefits may be attributed to improved drainage, moisture and aeration (Coville, 1910; Strik, 1993). In the Pacific Northwest, plant establishment is normally done by first incorporating Douglas-fir (*Pseudotsuga menziesii* M.) sawdust and N fertilizer prior to forming planting beds and planting (White et al, 2007). In addition, sawdust mulch after planting is commonly used to help control weeds and improve plant growth and yield (Krewer et al, 2009; White, 2006). Because of the low C:N ratio (≈ 800:1) of Douglas-fir sawdust, pre-plant N is incorporated along with the amendment to help sawdust decomposition (Julian et al., 2011).

Although, pruning to limit any fruit production until the third year after planting for optimum establishment is recommended (Strik and Buller, 2005), growers have started to obtain a light harvest by the second year for more rapid return on investment. The cost to establish blueberry may reach $22,500 per hectare (year zero) and cost of irrigation in the following year may reach around $6,000 per hectare (Julian et al, 2011), with little difference between double drip or sprinkler irrigation. A major advantage of drip is the capability of applying water-soluble fertilizers during irrigation (a.k.a. fertigation). Fertigation is becoming a common practice for many crops worldwide (Bar-Yosef, 1999; Kafkafi and Tarchiski, 2011).

Blueberry plants have low nutrient requirements compared to many other fruit crops (Hancock and Hanson, 1996) and tolerate relatively low levels of soil P, K, Ca, and Mg, as well as a high concentration of plant available metals such as Mn and Al (Korcak, 1988). Although blueberry has low nutrient requirements, the plant typically needs regular applications of fertilizers to maximize growth and fruit production (Bañados et al., 2012; Hanson and Hancock, 1996).

Due to plant adaptation to low pH, blueberry plants acquire primarily the ammonium form of N over the nitrate form (Claussen and Lenz, 1999), therefore, common fertilizers applied are ammonium sulfate and urea. Both are excellent sources of ammonium-N, however, urea is only half as acidifying as ammonium sulfate (Havlin et al., 2005). Thus, ammonium sulfate is recommended when soil pH is greater than 5.5, and urea or a mix of urea and ammonium sulfate when soil pH is less than 5.0 (Hart et al. 2006). The salinity index of a fertilizer is defined as the ratio of the increase of osmotic pressure of the salt solution produced by the fertilizer to that produced by the same weight of sodium nitrate. The salinity index produced by urea is half of the salinity produced by ammonium sulfate (1.6 vs. 3.2, respectively) (Havlin et al., 2005)

Depending on the planting age, location (region), and soil type current N rates recommended in blueberry range from 20 to 140 $kg \cdot ha^{-1}$ per season (British Columbia Ministry of Agriculture, 2012; Hanson, 2006; Hart et al, 2006). Applications may be either in the granular form or via fertigation. Granular applications are typically split into two or three applications during the spring (when N uptake is more active), spread along the planting bed and washed into the soil by rain or sprinkler irrigation (Bañados et al., 2012; Hart et al., 2006; Throop and Hanson, 1997). Whereas, fertigation is usually injected and applied into small frequent applications starting at leaf emergence and finishing ≈ 2 month before the end of the growing season (Bryla and Machado, 2011).

Fertigation often improves nutrient use efficiency resulting in more growth and yield than equivalent rates or the same growth and yield at even lower rates. There is less chance of over-fertilization due to the higher frequency of application and thus lower risk of salt stress. In addition, there is less compaction (no fertilizer spreader machinery needed) and reduced labor cost (Burt et al., 1998). However, disadvantages may include relatively more expensive soluble fertilizers, inclusion of injection equipment, more knowledge of fertilizer compatibility (potential drip emitter plugging), and more frequent applications (Bar-Yosef, 1999). With drip fertigation, nutrients are applied directly to the root zone and typically only 20% to 30% of the total soil volume is wet, resulting in a bulb-shaped wetting pattern where roots tend to concentrate (Bryla and Machado, 2011; Haynes, 1990).

Most blueberry fields have been irrigated historically using sprinklers; however, many new plantings are irrigated by drip, particularly in newer regions such as California, eastern Oregon and Washington (Strik and Yarborough, 2005). In western Oregon, blueberry plants irrigated by drip required approximately half as much water as those irrigated by sprinklers or microsprinklers (Bryla et al., 2011), but had inferior fruit quality (softer fruit with lower soluble solids concentrations; Bryla et al., 2009) and greater potential for root rot (Bryla and Linderman, 2007).

Microsprinklers have been used for irrigation in fruit trees such as apples and citrus (Dasberg, 1995; Fallahi et al, 2010) and are also becoming an alternative for irrigating blueberry plants grown on pine bark substrate in the southeastern United States (J. Williamson, personal communication). While drip fertigation targets relatively small soil volumes compared to traditional broadcast applications of granular fertilizers, fertigation through microsprinklers provides greater soil coverage and distributes nutrients more evenly than applications through most drip systems (Bar-Yosef, 1999; Elfving, 1982).

Recently, several manufacturers began developing modified drip products such as geotextile irrigation systems to deliver a broad band source of water and nutrients to plants, rather than the point sources produced by standard drip systems. A typical geotextile irrigation system has an impermeable base sheet or layer usually made of polyethylene or polypropylene, a drip line along that base, and a layer of geotextile fabric over the top of the drip line. The geotextile material facilitates mass flow and disperses irrigation water and nutrients over a larger area than drip, which potentially increases the efficiency of water and fertilizer applications (i.e., less deep percolation and nutrient leaching) (Charlesworth and Muirhead, 2003; Devasirvatham, 2008; Miller et al., 2000). A wider, uniform wetting pattern may be particularly beneficial in shallow-rooted crops such as blueberry (Bryla and Strik, 2007), because less water and nutrients will be lost below the root zone.

On the other hand, understanding what controls root production and longevity is important to minimize nutrient leaching and thus maximize fertilizer use efficiency (Eissenstat and Volder, 2005). The root system of plants is composed of individual roots of different ages whose function is absorbing water and nutrients. Root growth, architecture, and the capacity to relocate in favorable soil portions are highly affected by birth and death of its individual units (Eissenstat and Yanai, 1997; Pregitzer et al., 1993). Root construction and maintenance requires high amount of energy and thereby influence carbon allocation and mineral nutrient consumption; whereas, root death returns these resources to the soil (Jackson et al., 1997).

Ericoid species, including blueberry, are noted for having very fine, fibrous roots without root hairs. The blueberry root system is relatively shallow, remaining in the upper soil profile (Eck, 1988). In Oregon, Bryla and Strik (2007) found that most roots of three different cultivars were located in the top 20-30 cm of the soil profile. Similarly, a survey of 55 blueberry fields in Oregon showed that root length was generally greater in the upper 15 cm than in the lower 15-30 cm depth, but root biomass was greater at 15-30 cm than in the upper 15 cm. Spiers (1986) observed that mulching tended to concentrate roots in the upper 15 cm of soil and also resulted in more uniform root distribution. However, with drip irrigation most roots appear to remain near the drip line (Bryla and Strik, 2007; Eck, 1988; Gough, 1980;). Most blueberry roots are highly branched, with the finest roots reaching only 0.02 mm in diameter (Valenzuela-Estrada et al., 2008) or about twice the thickness of typical single-cell root hair (Barber, 1984).

Abbot and Gough (1987) showed that blueberry roots grow in a bimodal pattern throughout the year, with the first peak in early June and the second in September. More roots were produced when soil temperatures ranged from 7-20°C and was optimum at temperatures of 14-18°C, suggesting that root growth was not only controlled by carbohydrate availability, but also largely by soil temperature. Valenzuela-Estrada (2008) found no effect of reproductive stage on root production patterns during the three years of his study, and that root production normally increased in stage II of berry development (before berries turned blue).

There is inconsistency in soil N availability and root lifespan across fruit crops. This indicates that other factors such as, resource availability, root diameter, soil depth, date of birth, and morphology, also affect root lifespan (Eissentat and Yanai, 1997; McCormack and Guo, 2014). On the other hand, different application systems affect N concentration and root growth across the soil profile, particularly in the upper portion of the soil. Banding fertilizers localizes nutrients to a fraction of the root zone, while drip fertigation produces partial soil volume and a bulb-shaped pattern (Bar-Yosef, 1999; Haynes, 1990; Robinson, 1994). Regardless of the application system, fluctuations in nutrient concentration will depend on the application frequency. However, fertigation provides the benefit of reducing the salinity hazard in the root zone due to higher application frequency and improved nutrient distribution in the root zone (Bar-Yosef, 1999; Bryla and Machado, 2011). Granular nitrogen fertilizer application has shown to generate high nutrient concentration in solution (high electrical conductivity) and it may produce nutrient toxicity or nutrient imbalances. As a result, plants are affected by osmotic adjustments that require more energy consumption, which may reduce yield or produce lower quality fruit (Grattan and Grieve, 1999; Bryla and Machado, 2011).

In blueberry (*Vaccinium corymbosum* L.), median root lifespan ranged from 115-120 d (Valenzuela-Estrada et al., 2008), while mean lifespan was only 17 d in strawberry (*Fragaria* x *ananassa***)** (Atkinson, 1985). Adams et al. (2013) found no change in lifespan in sassafras (*Sassafras Albidum*) and tulip tree (*Liriodendron tulipifera*) with N addition, but increased lifespan of 40-48% in white poplar (*Populus tremuloides*). On the other hand, fine roots normally have a high uptake capacity, but at the same time high maintenance cost or a shorter lifespan; whereas increasing soil depth normally decreases mortality (Anderson et al., 2003; Eissenstat and Volder, 2005;). Nutrient uptake is normally positively correlated with the total root length for resource uptake, but the total length at any point in time is not only a result of root production, but also a result of cost and benefit from plants to keep roots alive (Adams et al., 2013; McCormack and Guo, 2014). Since root systems are not homogenous, the study of fine root dynamics needs to account for that variation (Baldi et al., 2010), particularly in crops with localized nutrient application. Several studies have determined that fine roots, which are the most active in absorbing water and nutrients, vary in lifespan, and may be replaced several times over the growing season (Eissenstat and Yanai, 1997, Volder et al., 2005).

Different ways to estimate root lifespan and morphology have been used in research studies, including monthly soil cores, N-balance approach, C-isotope approach, in-growth cores, and direct observation (rhizotrons and minirhizotrons) (Madji et al., 2005). Direct observation avoids assumptions used in other methods in relation to interpretation, such as simultaneous birth and death during a sampling interval, or spatial and sampling variation being confounded with temporal variation. However, the problem associated with minirhizotrons and other direct observation approaches is the artificial environment at the surface of the observation window which may change root behavior (Eissenstat and Yanai, 1997; Harper et al., 1992). Cox proportional hazard regression is commonly used in minirhizotron studies to evaluate simultaneously the effect of these factors on mortality and survivorship (Allison, 2010; Cox, 1972; Wells and Eissenstat, 2001).

Minirhizotron camera systems provide accurate assessment of new root production and lifespan at different depths in undisturbed soils. Such information is essential for a better understanding of current fertilization practices in commercial fields, while offering a great contribution in fertilization guidelines for blueberry. Root production represents a high energy cost to plants (Eissenstat and Yanai, 1997; McCormak and Guo, 2014); therefore, benefits in their construction (i.e. less carbon cost and/or longer root lifespan) related to N application practices may be associated not only to more efficient nutrient uptake, but also to improved aboveground plant performance.

Since blueberry roots are susceptible to high nutrient concentration (Coville, 1910; Townsend, 1973, Bryla and Machado, 2011), the application of nutrients through drip systems, has raised new questions about fertilizer placement for best plant establishment. With fertigation, nutrients are applied directly to a small wetted volume where roots are most concentrated, and both the concentration and balance of nutrients can be controlled more precisely (Bryla, 2011). However, depending on soil type, emitter discharge rate, and drip line placement (distance from plants), the application of nutrients from a point source may produce variations in soil nutrient distribution within the wetted volume and, as a result, affect root growth (Alva and Syvertsen, 1991; Bar-Yosef, 1999; Goldberg et al., 1971). Reduced salinity hazard with fertigation can be associated to the efficient displacement of salts to the periphery of the wetted soil volume and to the decrease in salinity in the root zone due to higher irrigation frequency (Bar-Yosef, 1999; Goldberg et al., 1971). Some studies have shown that fertigation results in lower salt accumulation immediately below the emitter becoming a site of higher root development (West et al., 1979). In addition, mobile nutrients displaced with water diffusion, tend to accumulate and, therefore, increase salinity in wetting front boundaries (i.e. NO_3-N and/or SO_4-S ions) (Bernstein and Francois, 1973). Goldberg et al., (1971) evaluated how ion distribution affected *Dianthus caryophyllus* L. roots under fertigation. They concluded that salt accumulation was higher in the first 0.2 m of soil depth between drip lines (i.e. in the root zone) when laterals where placed on each side of plants 0.45 m apart. As a result, root development was poor and shallow. Roots were concentrated in the first 0.1 m and tended to expand closer to the emitter where salinity was lower.

When high concentration of salts occurs in the root zone, ionic imbalances may retard root elongation (Roundy, 1985). Therefore, the root volume and soil explored are reduced and consequently decrease the amount of nutrients available to plants. In addition, accumulation of ions that move through mass flow, such as Ca^{+2}, NO_3^-, Na^+ and SO_4^{2-}, occurs when they are in excess, resulting in lower water potential and impaired root capability to uptake water. Another consequence is competition with other nutrients for cell wall absorption sites (Berstain and Kafkafi, 2002).

In addition to the common N fertilizers such as urea and ammonium sulfate in commercial blueberry production, the use of alternative fertilizers has also become popular, including controlled-release fertilizers (polymer-coated urea), urea sulfuric-acid, and humic acids. Polymer coated urea (PCU) is urea coated with a polymer and the N release is controlled mostly by temperature, coating thickness and composition. Since most of the environmental factors (temperature and moisture) that favor crop development are the same for coating degradation, the release period and pattern ideally will match crop N uptake. However, the release pattern and duration is difficult to accomplish due to temperature variation (Carson and Ozores-Hampton, 2013; Shaviv, 2001). The use of urea-sulfuric acid is well suited for fertigation in blueberry because ammonium is released quickly and sulfuric acid helps acidify the soil (Bryla et al., 2010), and it also can be used for other purposes such as to acidify the irrigation water (reducing clogging potential with carbonates and bicarbonates) (Boman and Obreza, 2012). On the other hand, the benefits of humic acids on plant growth have been reported in many studies (Rauthan and Schnitzer, 1981), and the majority of these benefits have been in low organic matter soils, sand culture or hydroponic production (Chen et al., 2004). Humic acids promote the conversion of nutrients into plant available forms such as P and Fe (Hopkins and Stark, 2003; Chen et al., 2004). The increased supply of micronutrients when humic acids are applied has been linked to chelate formation. Many reports have shown that humic acids have increased permeability of root plasma membrane, promoting the uptake of nutrients; while others have shown the auxin-type activity (hormone-like activity) (Senn et al., 1973). Similarly, other studies have reported benefits in various crops in agricultural conditions (Rose et al., 2014), but none of them to date have been reported in blueberry.

The objectives of this study were: 1) Compare the effects of fertigation with granular fertilizer in a maturing blueberry planting (years 3 to 7) on plant growth, yield and berry weight; 2) ascertain the impact of N fertigation and granular fertilizers on root production and lifespan using minirhizotrons in a maturing blueberry planting

(Years 4 to 6); 3) Evaluate the effects of N fertigation using a conventional drip configuration (with two laterals per row) and two alternative irrigation systems, geotextile tape and microsprinklers, on plant growth and early fruit production of six cultivars, including early-, mid, and late season production; 4) evaluate the impact of no pre-plant N incorporation; and 5) evaluate the effect of fertigation with different drip line placement, including one drip line or geotextile tape, two drip lines placed either near plants (narrow system) or far apart from plants (wide system); and the application of alternative fertilizers such as PCU, urea-sulfuric acid, and humic acids on plant nutrients, and shoot and root growth of highbush blueberry.

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Chapter 2 – Growth and Fruit Production of Highbush Blueberry Fertilized with Ammonium Sulfate and Urea Applied by Fertigation or as Granular Fertilizer

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Abstract

Fertigation with liquid sources of nitrogen (N) fertilizers, including ammonium sulfate and urea, were compared to granular applications of the fertilizers in northern highbush blueberry (*Vaccinium corymbosum* L. 'Bluecrop') during the first 5 years of fruit production (2008–2012). The planting was established in Apr. 2006 at a field site located in western Oregon. The plants were grown on raised beds and mulched every 2 years with sawdust. Liquid fertilizers were injected through a drip system in equal weekly applications from mid-April to early-August. Granular fertilizers were applied on each side of the plants, in three split applications from mid-April to mid-June, and washed into the soil using microsprinklers. Each fertilizer was applied at three N rates, which were increased each year as the plants matured (63–93, 133–187, and 200–280 $kg·ha^{-1}$ N), and compared to non-fertilized treatments (0 $kg·ha^{-1}$ N). Canopy cover, which was measured in 2008 only, and fresh pruning weight were greater with fertigation than with granular fertilizer, and often increased with N rate when the plants were fertigated, but decreased at the highest rate when granular fertilizer was applied. Yield also increased with N fertilizer and was 12% to 40% greater with fertigation than with granular fertilizer each year, as well as 17% greater with ammonium sulfate than with urea in 2011. The response of berry weight to the treatments was variable but decreased with higher N rates during the first 3 years of fruit production. Leaf N concentration was greater with fertigation in 4 out of 5 years and averaged 1.68% with fertigation and 1.61% with granular fertilizer. Leaf N was also often greater with ammonium sulfate than with urea and increased as more N was

applied. Soil pH declined with increasing N rates and was lower with granular fertilizer than with fertigation during the first 3 years of fruit production and lower with ammonium sulfate than with urea in every year but 2010. Soil electrical conductivity (EC) was < 1 $dS \cdot m^{-1}$ in each treatment but was an average of two to three times greater with granular fertilizer than with fertigation and 1.4–1.8 times greater with ammonium sulfate than with urea. Overall, total yield averaged 32–63 $t \cdot ha^{-1}$ in each treatment over the first 5 years of fruit production and was greatest when plants were fertigated with ammonium sulfate or urea at rates of at least 63−93 $kg \cdot ha^{-1}$ N per year.

Introduction

Northern highbush blueberry is well adapted to acidic soil conditions and often grows best in a pH range of 4.0–5.5 (Retamales and Hancock, 2012). Blueberry has low nutrient requirements compared to many other fruit crops (Hancock and Hanson, 1986), but typically needs regular applications of nitrogen (N) fertilizer to maximize growth and fruit production (Bañados et al., 2012; Hanson and Hancock, 1996). The plants acquire primarily the ammonium form of N (Claussen and Lenz, 1999) and, therefore, the most common N fertilizers applied to blueberry are ammonium sulfate and urea. Both are excellent sources of ammonium-N but the latter requires soil temperatures > 20 ^{o}C for complete breakdown and is only half as acidifying as ammonium sulfate (Havlin et al., 2005). Hart et al. (2006) suggest applying ammonium sulfate to blueberry when soil pH is > 5.5 and urea or a mix of urea and ammonium sulfate when soil pH is < 5.0.

Current N recommendations for blueberry range from 20–140 $kg \cdot ha^{-1}$ N per season, varying with the age of the planting, plant vigor, location (region), soil type, soil management (e.g., mulch applications), and inherent soil fertility (British Columbia Ministry of Agriculture, 2012; Hanson, 2006; Hart et al., 2006). Nitrogen is either applied as granular fertilizers or by fertigation. Granular fertilizers are typically spread along the rows and washed into the soil by rain or sprinkler irrigation. Two or three equal applications of granular N fertilizer are recommended each spring, which is when N uptake in blueberry is considered most active (Bañados et al., 2012; Throop and Hanson, 1997). Liquid fertilizers are usually injected and applied in small and frequent applications (e.g., once a week) through an irrigation system such as drip, starting at leaf emergence and finishing about 2 months prior to the end of the growing season, or beginning in May when irrigation is required on a regular basis (D.R. Bryla, personal communication). In the latter case, an initial application of granular fertilizer is often applied prior to fertigation, in March or April.

Current nutrient management guidelines for blueberry were developed based on granular fertilizers and may not be optimized for plants fertilized by fertigation. Bryla and Machado (2011) compared fertigation to granular applications of N fertilizer in a new planting of highbush blueberry and determined that fertigation was less efficient (i.e., less plant growth per unit of N applied) but safer (i.e., less salt damage and plant death) than granular fertilizer during the first 2 years of establishment. The objective of the present study was to extend this original study and compare the effects of fertigation to granular fertilizer during the first 5 years of fruit production (year 3–7). Both methods of fertilizer application were evaluated using ammonium sulfate or urea.

Materials and Methods

Study site. The study was conducted from 2008 to 2012 in a planting of 'Bluecrop' blueberry established in Apr. 2006 at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, Oregon (lat. 44°33′10″ N, long. 123°13′9″ W, 68 m elevation). Soil at the site was a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerolls) that had 2.4% organic matter content and an initial pH of 6.2 (Nov. 2005). Two applications of 670 $kg\cdot ha^{-1}$ of elemental sulfur were incorporated into the field at 6 and 10 months prior to planting, which reduced soil pH to 5.5 by planting (Horneck et al., 2004). Plants were obtained from a commercial nursery (Fall Creek Farm & Nursery, Jasper, OR) as 18-month-old container stock. The plants were transplanted onto 0.4-m high × 0.9-m wide raised planting beds at an in-row spacing of 0.76 m. Raised beds were formed using a tractor-powered bed shaper and were centered 3.0 m apart. A 7.5-cm deep × 1-m wide layer of aged (> 6 months) Douglas fir (*Pseudotsuga menziesii* Franco) sawdust was spread and rototilled into each row prior to shaping the beds (to increase soil organic matter content and improve drainage in the beds), and a 9-cm layer of the sawdust was applied as mulch on top of beds immediately after planting (primarily for weed control). The sawdust mulch was reapplied every 2 years. Grass alleyways (1.5-m wide) were planted between the beds and mowed every 1–2 weeks during the growing season. Weeds were controlled as needed using glyphosate herbicide at the base of beds and hand-weeding on the top of beds. No insecticides or fungicides were applied to the field.

Experimental design. An irrigation system was installed prior to planting and designed with a manifold to accommodate 16 different fertilizer treatments. The treatments were arranged in a split-plot design with a combination of two N sources (ammonium sulfate and urea) and two methods of fertilizer application (weekly fertigation and dry granular fertilizer applications) as main plots and four N rates as subplots. Each subplot consisted of one row of eight plants and was replicated six times. Only the middle six plants in each subplot were used for measurements. The planting contained a total of 952 plants and included 12 rows of treatment plots, with two border plants on each end, and two border rows on each side of the planting.

Liquid ammonium sulfate (9N–0P–0K–10S) and urea (20N–0P–0K) were applied by fertigation through a drip system. One line of drip tubing (GeoFlow, Charlotte, NC) was installed initially near the base of the plants during the first 3 years after planting (2006−2008), and a second line was added in Apr. 2009. When the second line was added, the lines were repositioned on each side of the row at a distance of ≈0.3 m from the base of the plants. The lines had 1.9 $L \cdot h^{-1}$ integrated pressure-compensating emitters located every 0.30-m and were covered with sawdust mulch after installation. The liquid fertilizers were injected at the manifold using

Venturi-type injectors (Mazzei Model 584 Injector Corp., Bakersfield, CA). Plants were fertigated weekly, beginning in mid-April each year and continuing until early August. Fertigation was not applied during the latter part of the growing season (i.e., mid-August to late September) because N applications in late summer reduce fruit bud set in blueberry and increase the potential for winter freeze damage (Hart et al., 2006).

Granular ammonium sulfate (21N–0P–0K–24S) and urea (46N–0P–0K) were applied by hand once a month from April to June in three equal applications per year. The fertilizers were spread along the row in a 20-cm-wide band on each side of the plants and then immediately washed into the soil using 22.7 $L \cdot h^{-1}$ hanging fan-jet microsprinklers (DC Series, Bowsmith, Exeter, CA). The microsprinklers were attached to a trellis wire (suspended in the middle of the row at a height of 1.5 m) and located directly between each plant in the treatment plot (i.e., six microsprinklers per plot). The system was operated at a pressure of 100−140 kPa. Each microsprinkler produced approximately a 2.3-m diameter, circular-wetting pattern.

Both the liquid and granular fertilizers were applied at initial rates of 0, 50, 100, and 150 $kg \cdot ha^{-1}$ N during the first 2 years after planting (2006–2007) and increased (as the plants matured) to 0, 67, 133, and 200 $kg \cdot ha^{-1}$ N in year 3 (2008); 0, 75, 150, and 225 $kg \cdot ha^{-1}$ N in year 4 (2009); 0, 83, 167, and 250 $kg \cdot ha^{-1}$ N in year 5 (2010); and 0, 93, 187, and 280 $kg \cdot ha^{-1}$ N in years 6 and 7 (2011−2012). Since treatments with no N (0 $kg \cdot ha^{-1}$ N) were identical within the two fertilizer methods (fertigation and granular fertilizer), only one of each was used for measurements in the present study; the others were utilized to test additional N sources (unpublished results).

Plants were irrigated from early May to late September each year using the drip system for the fertigated treatments and the microsprinklers for the granular treatments. Irrigation was scheduled three to seven times per week based on weather and daily estimates of crop evapotranspiration (Bryla, 2011b). Precipitation and crop evapotranspiration were obtained at least weekly from a nearby AgriMet Cooperative Agricultural Weather Network weather station (http://www.usbr.gov/pn/agrimet/agrimetmap/crvoda.html). Water application was monitored using water meters (Model SRII; Sensus, Raleigh, NC) installed at the inflow of each treatment. Additional water (≈5 $mm \cdot week^{-1}$) was also applied for fertigation in April each year, and all treatments, including those with no N or with microsprinklers, were irrigated using the same amount of water. The pH of the irrigation water was 6.9–7.0 over the course of the growing season, and electrical conductivity (EC) was < 0.1 $dS \cdot m^{-1}$.

Measurements. Canopy cover was estimated on 28 Aug. 2008 from digital images captured using an ADC multispectral camera (TetraCam Inc., Chatsworth, CA). The camera was suspended from a marked trellis wire located ≈2.5 m above the planting bed. Images were collected from every other plant of the center six plants in each treatment plot, for a total of 288 images. Percent live cover in each image was determined using software provided by the camera manufacturer (Pixelwrench and Briv32). Care was taken to ensure that the image area always exceeded canopy width in each image. Any cover by weeds or the grass alleyway was cleaned from the images prior to analysis using Adobe Photoshop v. 5.0 (Adobe Systems Inc., San Jose, CA). Live cover was converted to total percent canopy cover based on the proportion of the field covered by each image (1.2 m $\times$ 1.5 m). By 2009, differences in plant size were no longer discernible by measuring canopy cover. At this point, the branches overlapped between adjacent plants within each row, and the measurements were discontinued.

Plants were pruned in January or February each year. To encourage vegetative growth during establishment, all fruit buds were removed during the first 2 years of pruning, delaying fruit production until the third year after planting in 2008 (Strik and Buller, 2005). The prunings were weighed fresh in each plot every winter. Fruit were hand-picked three or four times per year from mid-July to early-August and weighed each time to determine the total yield in each treatment plot. A random sample of 100 berries was also weighed at each harvest to calculate the average berry weight in each plot.

Leaf samples were collected for N analysis during the first week of August each year (Hart et al., 2006). Six recently mature leaves were sampled and pooled from the center six plants in each plot, oven-dried at 70 ^{o}C, ground, and analyzed for total N using a combustion analyzer (model CNS-2000; LECO Corp., St. Joseph, MI). Each sample was also analyzed for P, K, Ca, Mg, S, Fe, B, Cu, Mn, and Zn using an inductively coupled plasma optical emission spectrometer (Optima 3000DV; Perkin Elmer, Wellesley, MA) following microwave digestion in 70% (v/v) nitric acid (Gavlak et al., 2005). Each year, the concentration of these additional nutrients were similar among the treatments and always within the range recommended for highbush blueberry (Hart et al., 2006)

Soil samples were collected during the third week of July each year and analyzed for pH and EC. A 30-cm long × 2-cm diameter soil probe (JMC Backsaver, N-2 Handle, Newton, IA) was used to collect the soil samples to a depth of 0−20 cm. Each plot was sampled on each side of the planting bed at a distance of ≈30 cm from the center of the row (i.e., directly near a drip emitter in the fertigated plots and where the fertilizer was banded in the granular plots). Holes created by sampling were immediately refilled using soil collected from the border rows, and care was taken to sample a different location each year. Soil samples were air-dried, ground to pass through a 2-mm sieve, and measured for pH and EC following a 1:2 soil:water (w/w) method (Jackson, 1958; Jones, 2001).

Data analysis. Data were analyzed by analysis of variance (ANOVA) using the PROC MIXED procedure in SAS (Version 9.3 software, SAS Institute, Cary, NC). In order to create a balanced factorial treatment structure, the non-fertilized plants (0 $kg \cdot ha^{-1}$ N) irrigated by drip and microsprinklers were excluded from the ANOVA. Orthogonal contrasts were used to make independent linear comparisons between the two non-fertilized treatments and factorial comparisons among N rates and two-way interactions with N rate (Gomez and Gomez, 1984). To achieve homogeneity of variance in the data, soil EC was log-transformed prior to analysis and back-transformed for presentation. Means were separated at the 0.05 level using the Tukey-Kramer Honestly Significant Difference (HSD) test.

Results

Plant growth. Analysis of the canopy cover images revealed that the plants were significantly larger with fertigation than with granular fertilizer during the first year of fruit production in 2008 ($P < 0.0001$; Figure 2-1). A significant difference between the non-fertilized plants ($P = 0.0073$) suggests that at least some of the difference between the two fertilizer methods may have been due to how the plants were irrigated. Even without N (0 $kg \cdot ha^{-1}$ N), plants irrigated by drip (used for fertigation) had more canopy cover than those irrigated by microsprinklers (used for granular fertilizers). The interaction between the method of fertilizer application and N rate was also significant ($P = 0.0199$) due the fact that canopy cover increased slightly with N rate when the plants were fertigated but decreased at the highest N rate (200 $kg \cdot ha^{-1}$ N) when granular fertilizer was applied. Canopy cover was not affected by N source (ammonium sulfate and urea) or any interactions with N source in 2008.

Analysis of the pruning weights suggested that plant growth continued to be greater with fertigation than with granular fertilizer each year and, in 3 out of 5 years (2008, 2011, and 2012), increased linearly with N rate when plants were fertigated but decreased at the highest N rate when granular fertilizer was applied (Table 2-1). Pruning weight was also affected by N rate in 2009, but in this case, the increase was quadratic, regardless of the fertilizer method ($P = 0.0260$).

Fruit production. Yield was similar between non-fertilized plants irrigated by drip or microsprinklers each year but was always greater by 12% to 40% with fertigation than with granular fertilizer (Table 2-2). Significant interactions with method indicated that yield was also lower with ammonium sulfate than with urea when granular fertilizer was applied in 2008, and was similar among N rates with fertigation but decreased at the highest N rate when granular fertilizer was applied in 2009. Yield also decreased linearly with N rate in 2010 and was 17% greater with ammonium sulfate than with urea in 2011. After 5 years, total yield was 8.2 $t \cdot ha^{-1}$ greater with fertigation than with granular fertilizer but was similar between the fertilizer sources and among the N rates (Table 2-2).

Berry weight was greater with fertigation than with granular fertilizer in 2008, but was either similar between the methods or lower with fertigation the following years (Table 2-2). Berry weight also decreased linearly with N rate in 2008–2010 (Table 2-2). In 2010, berry weights were below average in all treatments (1.3–1.5 g/berry), indicating the plants were over cropped, and perhaps explaining why treatments with the highest yields such as the fertigated plants had the lowest berry weights. However, berry weight was also lower with drip than with microsprinklers in the non-fertilized plants in 2010, suggesting that irrigation could have also affected the berry weights that year (Table 2-2).

Leaf N concentrations. Leaf N concentrations ranged from 1.16% to 1.88% (Table 2-3). In 4 out of 5 years, leaf N was greater with fertigation than with granular fertilizer, although, in one of those years (2008), was only greater with fertigation when ammonium sulfate was applied. Leaf N was also greater, in most cases, with ammonium sulfate than with urea and, each year, increased linearly with N rate. Two-way interactions indicated that leaf N responded more to N rate with fertigation than with granular fertilizer in 2009 and with ammonium sulfate than with urea in 2012 (Table 2-3); a three-way interaction in 2011 revealed that leaf N was greater with fertigation and ammonium sulfate than the other treatments at the lower N rates, but was similar among each treatment except granular urea at the highest N rate (Figure 2-2).

Leaf N concentration was negatively correlated to soil pH each year (r^2 = -0.59 to -0.87; $P < 0.001$) and positively correlated to yield every year except 2009 (r^2 = 0.30–0.75 in 2008 and 2010–2012; $P < 0.05$).

Soil conditions. Depending on the year and treatment, soil pH ranged from 4.2 to 6.9 (Table 2-4). On average, the values were 0.2−0.4 units lower with granular fertilizer than with fertigation in 2008 through 2010, 0.3−1.0 units lower with ammonium sulfate than with urea in every year except 2010, and 0.7–0.8 units lower with microsprinklers than with drip in the non-fertilized plants in 2011 and 2012. Soil pH also decreased with N rate each year, particularly with fertigation in 2008, and with ammonium sulfate in 2011. By 2012, soil pH was lowest at each N rate when the plants were fertigated with ammonium sulfate (pH 4.2–4.9) and highest when the plants fertigated with urea (pH 5.3– 6.7) (Figure 2-3).

Soil EC was greater with granular fertilizer and ammonium sulfate in most years (but not in 2010) and increased with N rate each year (Table 2-4). In some years, soil EC was also slightly greater with microsprinklers than with drip in the non-fertilized plants, which may have contributed to differences in the fertilizer treatments. Interactions indicated that the response of EC to N rate was greater when granular fertilizer or ammonium sulfate was applied in 2011, and that EC was only greater with ammonium sulfate when the plants were fertigated in 2012 (Table 2-4).

Discussion

Fertigation with ammonium sulfate or urea consistently increased yield by 12% to 40% over the use of granular fertilizer applications during the first 5 years of fruit production. Ehret et al. (2014) found similar results in ‘Duke’ blueberry in British Columbia, and likewise concluded that fertigation with ammonium sulfate was more effective than broadcast applications of the fertilizer. In both cases, higher yields with fertigation were associated with greater plant growth, especially during the first 3-4 years after planting. The benefits of fertigation in blueberry are consistent with other high-value fruit and vegetables crops, including apple [*Malus* × *sylvestris* (L.) Mill. var. *domesticus* (Borkh.) Mansf.], orange (*Citrus sinensis* Osb.), and bell pepper (*Capsicum annum* L.), which all had greater production when N fertilizer was injected through a drip system than when broadcast at the same rate on the soil surface (Dasberg et al., 1988; Haynes, 1986; Nielsen et al., 1999).

In most cases, N fertilizer increased yield compared to no N in the present study, indicating that N was limited at the site. However, yield did not increase with increasing N rates and, in fact, declined in 2010 at the highest N rate (i.e., 250 $kg\cdot ha^{-1}$ N) when granular fertilizer was applied. Several studies have suggested that high N rates may be detrimental to fruit production in highbush blueberry, including ‘Wolcott’ blueberry in North Carolina (Ballinger et al., 1963), ‘Collins’ blueberry in Arkansas (Clark et al., 1988), and ‘Bluecrop’ blueberry in Michigan (Hanson and Retamales,

1992) and Oregon (Bañados et al., 2012). In each case, N fertilizer was applied in the granular form in one or more applications per season. Using the blueberry plants from the present study, Bryla and Machado (2011) found that plant growth also declined with higher rates of granular ammonium sulfate during the first 2 years after planting and suggested that less growth was due to high salinity from the fertilizer (up to 8 $dS \cdot m^{-1}$). They concluded that fertigation was safer in terms of soil salinity (always ≤ 1 $dS \cdot m^{-1}$) but was less efficient at lower N rates than granular fertilizer because at least half of the fertilizer delivered through drip emitters was located outside of the root zone. However, once the plants grew and developed a larger root system, we found in the present study that only 63−93 $kg \cdot ha^{-1}$ N was needed to maximize fruit production with either fertigation or granular fertilizer (Table 2-2). The larger plants also appeared to be more tolerant of higher granular N rates than during first 2 years after planting (Bryla and Machado, 2011), and they showed no evidence at this point of salinity stress such as wilting, leaf reddening, or leaf necrosis (Caruso and Ramsdell, 1995).

Fruit size, measured in terms of berry weight, was also affected by method of N application, although not consistently from year to year. For example, fertigation produced larger berries than granular fertilizer during the first year of fruit production but smaller berries in the third year. Ehret et al. (2014) also obtained smaller berries with fertigation than with granular ammonium sulfate in ‘Duke’ blueberry and suggested that reduced fruit size may have been a result of greater flower production with fertigation, which then resulted in heavier crops loads. Heavy crop loads reduce fruit size in blueberry (Strik et al., 2003) and probably explains why berry weight was lower in the third year than any other year, particularly with fertigation (1.2−1.4 g/berry). Interestingly, fruit size also decreased with N rate during the first 3 years of fruit production in the present study, despite similar or lower yields at the higher rates. Excess N results in greater vegetative growth in blueberry and can delay fruit development (Bañados et al., 2012).

Leaf N concentration increased with N rate and, in general, was greater with fertigation than with granular fertilizer, or greater with ammonium sulfate than with urea. Leaf N increased by an average of 0.5% with N fertilizer, but it was always below the recommended range of 1.76% to 2.00% (Hart et al., 2006) at the lower N rates, and it never exceeded the range at the highest N rate. Leaf N concentration averaged 1.68% with fertigation and 1.61% with granular fertilizer and was often higher with ammonium sulfate than with urea. Fertigation enhances N uptake in many crops by improving the timing and placement of the N fertilizer and, therefore, often increases leaf N concentration relative to granular fertilizer (Bryla et al., 2010; Bryla, 2011a, Bryla and Vargas, 2014). Ammonium sulfate may also increase N uptake relative to urea due to lower soil pH and increased availability of NH_4-N (Haynes, 1990), both of which are beneficial in blueberry. Weekly measurements of the soil solution at the site indicated that NH_4-N concentrations were three times greater with ammonium sulfate than with urea when the plants were fertigated, and nine times greater when the plants were grown with granular fertilizer (Machado et al., 2014).

While both of the fertilizers used in this study reduced the soil pH, pH was lower when the plants were fertilized with ammonium sulfate than with urea.

Ammonium sulfate is known to be more acidifying than urea, because it produces twice as many H^+ ions from nitrification (Hart el al., 2013), and it is less prone to leaching (Clothier and Sauer, 1988; Haynes, 1990). Soil pH also declined with increasing N rates and averaged 5.1–5.7 with granular fertilizer and 5.2–5.9 with fertigation. Soil pH was often above the range of 4.0–5.5 recommended for northern highbush blueberry, particularly at the lower N rates. However, the measurements were based on bulk soil samples (0–20 cm depth) and, therefore, do not necessarily represent the pH in the rhizosphere. In most drip-irrigated crops, including blueberry, roots concentrate near the drip emitters (Bryla, 2011b). Intensive sampling in a nearby blueberry planting fertigated with urea indicated that, while the bulk soil pH was 6.4, soil pH at a depth of 5 cm directly under the drip emitter was 4.9 (Almutairi et al., 2013).

Soil EC increased as a function of N rate and was often greater with granular fertilizer than with fertigation, or greater with ammonium sulfate than with urea. Electrical conductivity is a good indicator of soil salinity and tends to increase rapidly with high concentrations of N fertilizer (Bunt, 1988). In irrigation water or soil solution, EC increases linearly at a rate of 2 $dS \cdot m^{-1}$ for each $g \cdot L^{-1}$ of ammonium sulfate (Machado et al., 2014). Soil solution EC also increases with urea, but generally less so than with ammonium sulfate (Machado et al., 2014). While EC never exceeded 1 $dS \cdot m^{-1}$ in any treatment and was lower than reported previously with granular fertilizers, the differences among treatments were consistent (Bryla and Machado, 2011; Bryla et al., 2010; Machado et al., 2014). Soil EC in our previous reports was measured throughout the growing season, including following each fertilizer application, using soil solution samplers installed at a depth of 5–10 cm. In either case, the results indicate that both fertigation and the use of urea reduce soil salinity relative to granular ammonium sulfate and, therefore, may be safer alternatives, particularly in younger blueberry plants.

Conclusion

Fertigation resulted in more plant growth and yield than granular applications of N fertilizers during the first 5 years of fruit production. Plant growth was also greater at higher N rates each year. However, higher N rates did not improve yield in any year and resulted in smaller berries during the first 3 years of production and less yield during the third year when granular fertilizers were applied. Thus, 67–93 $kg \cdot ha^{-1}$ N was adequate to maximize fruit production, whether N was applied by fertigation or as granular fertilizer. These rates are lower than the 100–160 $kg \cdot ha^{-1}$ N recommended by Hart et al. (2006). Typical blueberry yields in western Oregon range from 2–16 $t \cdot ha^{-1}$ during the first 5 years and can reach more than 25 $t \cdot ha^{-1}$ by full production (typically 7–8 years after planting) (Julian et al., 2011). Yields in the present study were normal for the region and ranged from 2–4 $t \cdot ha^{-1}$ during the first year of fruit production and increased to 14–20 $t \cdot ha^{-1}$ (with N fertilizer) by the fifth year.

Ammonium sulfate resulted in higher leaf N concentrations, as well as lower soil pH, than urea, and increased cumulative yield by 10% when the fertilizers were applied by fertigation. However, ammonium sulfate also increased soil EC more than urea and resulted in lower yields during the first 2 years than any other treatment when applied as a granular fertilizer. Thus, urea may be preferable initially when using granular fertilizers.

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Tables and Figures

Table 2-1 Effects of different methods, sources, and rates of N fertilizer on fresh pruning weight of 'Bluecrop' blueberry during the first 5 years of fruit production (2008−2012) in Oregon.

Treatment	Pruning wt (kg/plant)							
	2008		2009	2010	2011		2012	
Non-fertilized plants								
Drip	0.12		0.08	0.26	0.15		0.12	
Microsprinklers	0.11		0.09	0.27	0.15		0.15	
Significance	NS		NS	NS	NS		NS	
Fertilized plants[z]								
Method (M)								
Fertigation	0.29		0.17	0.50	0.28		0.44	
Granular fertilizer	0.17		0.13	0.34	0.21		0.32	
Significance	***		***	***	***		***	
Source (S)								
Ammonium sulfate	0.22		0.15	0.42	0.25		0.38	
Urea	0.24		0.15	0.42	0.24		0.37	
Significance	NS		NS	NS	NS		NS	
N rate (N)	Fertig.	Gran.			Fertig.	Gran.	Fertig.	Gran.
67–93 $kg \cdot ha^{-1}$ N	0.26	0.18	0.13	0.43	0.25	0.23	0.36	0.30
133–187 $kg \cdot ha^{-1}$ N	0.28	0.18	0.16	0.43	0.27	0.23	0.44	0.37
200–280 $kg \cdot ha^{-1}$ N	0.33	0.15	0.16	0.40	0.31	0.18	0.50	0.28
Significance	$M \times N_L$**		Q^*	NS	$M \times N_L^{***}$		$M \times N_L^{***}$	

[z]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 $kg \cdot ha^{-1}$ N in 2008; 75, 150, and 225 $kg \cdot ha^{-1}$ N in 2009; 83, 167, and 250 $kg \cdot ha^{-1}$ N in 2010; and 93, 187, and 280 $kg \cdot ha^{-1}$ N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as 'Fertig.' and 'Gran.', respectively. There were no significant two-way interactions with N source, or any significant three-way interactions among the test factors.

$^{NS, *, **, ***}$Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; 'L' and 'Q' indicate significant linear and quadratic responses to N rate, respectively; and '$M \times N_L$' indicates that a significant interaction between method and N rate is primarily due to the difference in the linear part of the pruning weight responses to N rate of the two methods.

Table 2-2 Effects of different methods, sources, and rates of N fertilizer on yield and berry weight of 'Bluecrop' blueberry during the first 5 years of fruit production (2008−2012) in Oregon.

	Yield ($t \cdot ha^{-1}$)						Berry wt (g)				
Treatment	2008	2009	2010	2011	2012	Total	2008	2009	2010	2011	2012
Non-fertilized plants											
Drip	2.2	5.6	9.9	5.7	9.5	32.5	1.59	1.75	1.38	1.98	1.97
Microsprinklers	2.5	6.5	10.5	6.7	10.5	36.6	1.63	1.84	1.51	2.11	1.99
Significance	NS	NS	NS	NS	NS	NS	NS	NS	***	NS	NS
Fertilized plants[z]											
Method (M)											
Fertigation	3.5	8.2	15.1	12.8	17.6	57.2	1.69	1.65	1.30	2.04	2.19
Granular fertilizer	2.5	7.2	12.5	11.5	15.3	49.0	1.56	1.66	1.47	2.06	2.21
Significance	***	**	***	*	**	***	***	NS	***	NS	NS
Source (S)	Fertig. Gran.										
Ammonium sulfate	3.6 a[y] 2.2 c	7.4	14.0	13.1	17.1	54.5	1.63	1.64	1.36	2.04	2.22
Urea	3.5 a 2.9 b	8.0	13.6	11.2	15.7	51.7	1.62	1.67	1.41	2.06	2.17
Significance	$M \times S^{*}$	NS	NS	**	NS	NS	NS	NS	**	NS	NS
N rate (N)		Fertig. Gran.									
67–93 $kg \cdot ha^{-1}$ N	3.2	8.2 7.7	14.8	12.4	17.0	55.4	1.69	1.71	1.41	2.10	2.16
133–187 $kg \cdot ha^{-1}$ N	3.0	7.7 7.7	13.6	12.0	16.0	52.4	1.60	1.66	1.39	2.04	2.21
200–280 $kg \cdot ha^{-1}$ N	2.9	8.5 6.3	12.9	12.0	16.3	51.6	1.58	1.58	1.35	2.01	2.22
Significance	NS	$M \times N_L^{**}$	L^{*}	NS	NS	NS	L^{***}	L^{*}	L^{*}	NS	NS

[z]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 $kg \cdot ha^{-1}$ N in 2008; 75, 150, and 225 $kg \cdot ha^{-1}$ N in 2009; 83, 167, and 250 $kg \cdot ha^{-1}$ N in 2010; and 93, 187, and 280 $kg \cdot ha^{-1}$ N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N source, method and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as 'Fertig.' and 'Gran.', respectively. There were no significant interactions between N source and N rate, or any significant three-way interactions among the test factors.

[y]Means (n = 6) followed by the same letter are not significantly different, according to Tukey's HSD test ($P \leq 0.05$).

[NS, *, **, ***]Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; 'L' indicates a significant linear response to N rate; and '$M \times N_L$' indicates that a significant interaction between method and N rate is primarily due to the difference in the linear part of the yield responses to N rate of the two methods.

Table 2-3 Effects of different methods, sources, and rates of N fertilizer on leaf N concentration in 'Bluecrop' blueberry during the first 5 years of fruit production (2008−2012) in Oregon.

Treatment	Leaf N (%) 2008		2009		2010	2011	2012	
Non-fertilized plants								
Drip	1.34		1.35		1.16	1.23	1.23	
Microsprinklers	1.43		1.31		1.27	1.30	1.29	
Significance	**		NS		*	NS	NS	
Fertilized plants[z]								
Method (M)								
Fertigation	1.71		1.72		1.58	1.72	1.69	
Granular fertilizer	1.64		1.73		1.46	1.64	1.57	
Significance	***		NS		***	***	***	
Source (S)	Fertig.	Gran.						
Ammonium sulfate	1.79 a[y]	1.64 b	1.76		1.57	1.74	1.67	
Urea	1.64 b	1.64 b	1.70		1.48	1.62	1.59	
Significance	M × S***		***		**	***	***	
N rate (N)			Fertig.	Gran.			A. sulf.	Urea
67–93 kg·ha^{-1} N	1.57		1.62	1.64	1.45	1.61	1.56	1.44
133–187 kg·ha^{-1} N	1.69		1.71	1.77	1.54	1.70	1.74	1.61
200–280 kg·ha^{-1} N	1.76		1.82	1.79	1.59	1.73	1.72	1.70
Significance	L***		M × N_L***		L***	M × S × N**	S × N_L*	

[z]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 kg·ha^{-1} N in 2008; 75, 150, and 225 kg·ha^{-1} N in 2009; 83, 167, and 250 kg·ha^{-1} N in 2010; and 93, 187, and 280 kg·ha^{-1} N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N source, method and N rate, or N source and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as 'Fertig.' and 'Gran.', respectively, and the column heading for ammonium sulfate is abbreviated as 'A. sulf.'. Results of a significant three-way interaction on leaf N in 2011 are presented in Figure 2-2. In no instance did N rate interact significantly with both method and N source.

[y]Means (n = 6) followed by the same letter are not significantly different, according to Tukey's HSD test ($P \leq 0.05$).

[NS, *, **, ***]Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; 'L' indicates a significant linear response to N rate; and 'M × N_L' and 'S × N_L' indicate that a significant interaction between method and N rate and source and N rate are primarily due to the difference in the linear part of the leaf N responses to N rate of the two methods and N sources, respectively.

Table 2-4 Effects of different methods, sources, and rates of N fertilizer on soil pH and electrical conductivity (EC) at a depth of 0–20 cm in a field of 'Bluecrop' blueberry during the first 5 years of fruit production (2008–2012) in Oregon.

	Soil pH							Soil EC ($dS\cdot m^{-1}$)								
Treatment	2008		2009	2010	2011		2012	2008	2009	2010	2011				2012	
Non-fertilized plants																
Drip	6.2		6.1	5.9	6.8		6.9	0.09	0.09	0.16	0.07				0.06	
Microsprinklers	6.1		6.1	6.0	6.1		6.1	0.17	0.10	0.12	0.10				0.19	
Significance	NS		NS	NS	***		***	*	NS	NS	**				***	
Fertilized plants[y]																
Method (M)																
Fertigation	5.9		5.5	5.5	5.7		5.3	0.13	0.19	0.37	0.14				0.15	
Granular fertilizer	5.6		5.1	5.3	5.7		5.3	0.39	0.44	0.48	0.34				0.33	
Significance	**		**	*	NS		NS	***	***	NS	***				***	
Source (S)															Fertig.	Gran.
Ammonium sulfate	5.6		5.1	5.3	5.4		4.8	0.30	0.39	0.46	0.32				0.21 b[x]	0.33 a
Urea	5.9		5.5	5.5	6.0		5.7	0.22	0.23	0.38	0.16				0.09 c	0.32 a
Significance	**		**	NS	***		***	*	**	NS	***				$M \times S^{**}$	
N rate (N)	Fertig.	Gran.			A. sulf.	Urea					Fertig.	Gran.	A. sulf.	Urea		
67–93 $kg\cdot ha^{-1}$ N	6.3	5.8	5.7	5.6	6.0	6.1	5.8	0.20	0.18	0.25	0.11	0.14	0.14	0.11	0.16	
133–187 $kg\cdot ha^{-1}$ N	6.0	5.6	5.3	5.4	5.3	5.9	5.1	0.24	0.34	0.43	0.16	0.46	0.44	0.18	0.28	
200–280 $kg\cdot ha^{-1}$ N	5.5	5.5	4.9	5.2	5.0	5.8	4.9	0.35	0.42	0.59	0.16	0.42	0.39	0.19	0.27	
Significance	$M \times N_L^{**}$		L^{***}	L^{***}	$S \times N_L^{***}$		$M \times S \times N^{*}$	L^{*}	L^{***}	L^{***}	$M \times N_Q^{***}$		$S \times N_Q^{***}$		Q^{**}	

[z]Precipitation during the month prior to sampling was minimal, totaling only 1–4 mm in 2008, 2010, and 2012, and 19 and 27 mm, respectively, in 2009 and 2011.

[y]Two N sources (ammonium sulfate and urea) were applied by two methods (fertigation to plants irrigated by drip or granular fertilizer to plants irrigated by microsprinklers) at rates of 67, 133, and 200 $kg\cdot ha^{-1}$ N in 2008; 75, 150, and 225 $kg\cdot ha^{-1}$ N in 2009; 83, 167, and 250 $kg\cdot ha^{-1}$ N in 2010; and 93, 187, and 280 $kg\cdot ha^{-1}$ N in 2011 and 2012. Only main effects are presented in the absence of significant interactions. When interactions between two test factors (i.e., method and N source, method and N rate, or N source and N rate) are significant, the means of each factor is presented. In these cases, the column headings for fertigation and granular fertilizer are abbreviated as 'Fertig.' and 'Gran.', respectively, and the column heading for ammonium sulfate is abbreviated as 'A. sulf.'. Results of a significant three-way interaction on soil pH in 2012 are presented in Figure 2-3. In no instance did N rate interact significantly with both method and N source.

[x]Means (n = 6) followed by the same letter are not significantly different, according to Tukey's HSD test ($P \leq 0.05$).

[NS, *, **, ***]Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively; 'L' and 'Q' indicate a significant linear or quadratic response to N rate, respectively; and '$M \times N_L$', '$S \times N_L$', '$M \times N_Q$', and '$S \times N_Q$' indicate that a significant interaction between method and N rate and source and N rate are primarily due to the difference in the linear or quadratic part of the soil pH and EC responses to N rate of the two methods and N sources, respectively.

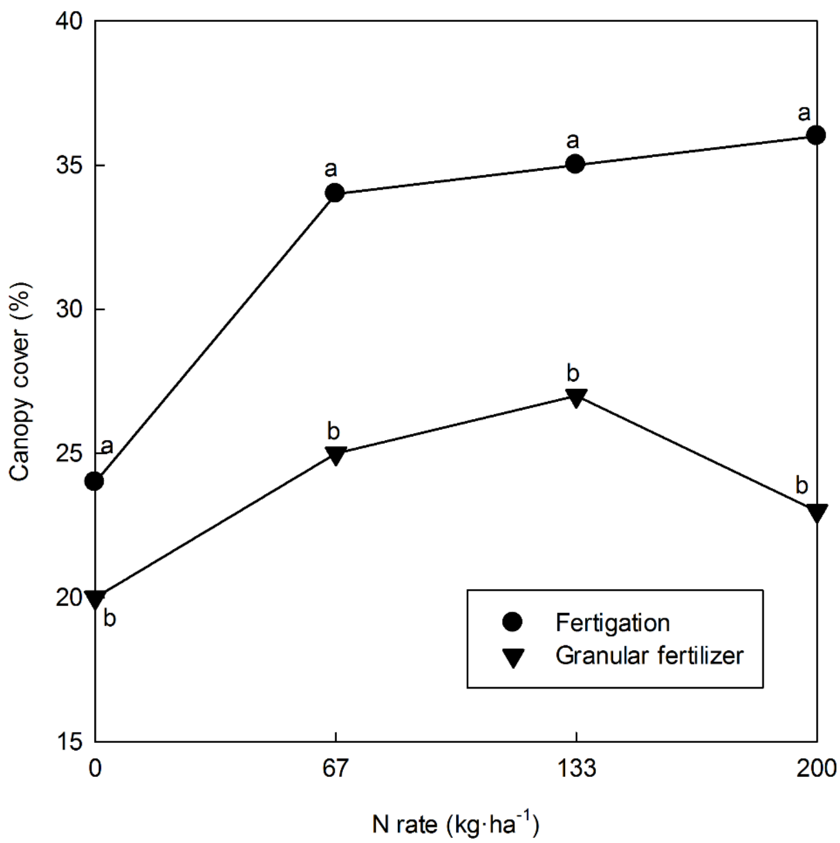

Figure 2-1 Canopy cover of 'Bluecrop' blueberry during the first year of fruit production (2008) in Oregon. Plants were non-fertilized or fertilized with three rates of N applied by fertigation or as granular fertilizer each year. Each symbol represents the mean of six replicates. Means with the same letter within each N rate are not significantly different, according to Tukey's HSD test ($P \leq 0.05$).

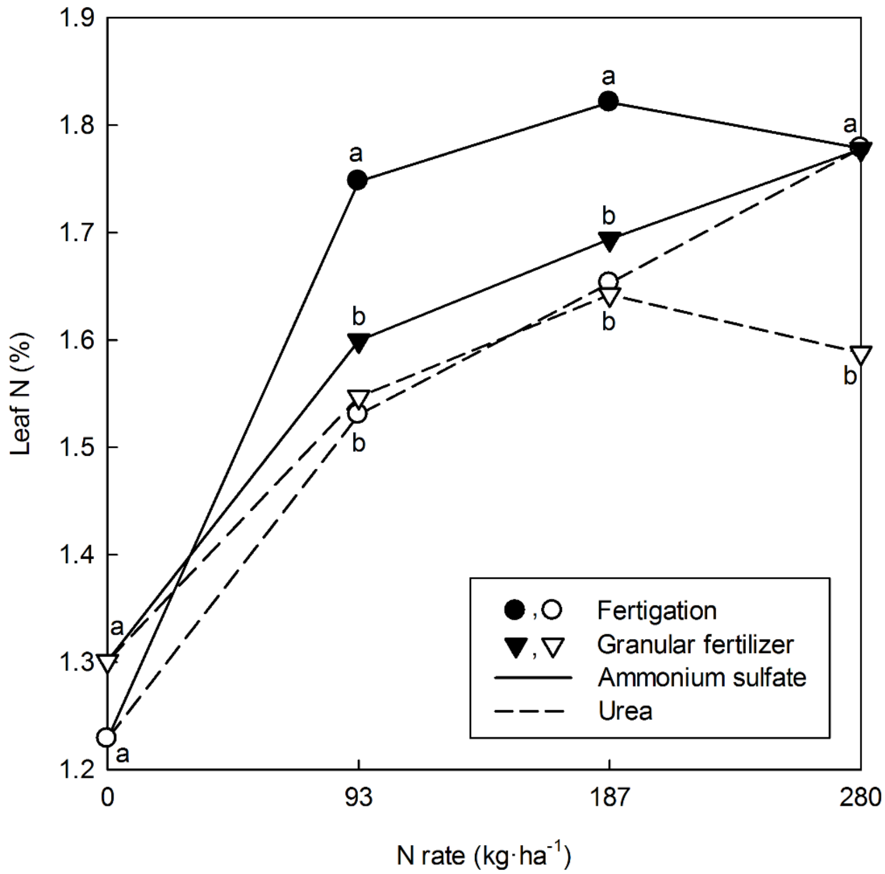

Figure 2-2 Leaf N concentration in 'Bluecrop' blueberry during the fourth year of fruit production (2011) in Oregon. Plants were non-fertilized or fertilized with three rates of ammonium sulfate or urea applied by fertigation or as granular fertilizer each year. Each symbol represents the mean of six replicates. Means with the same letter within each N rate are not significantly different, according to Tukey's HSD *test* (P $\leq$ *0.05).*

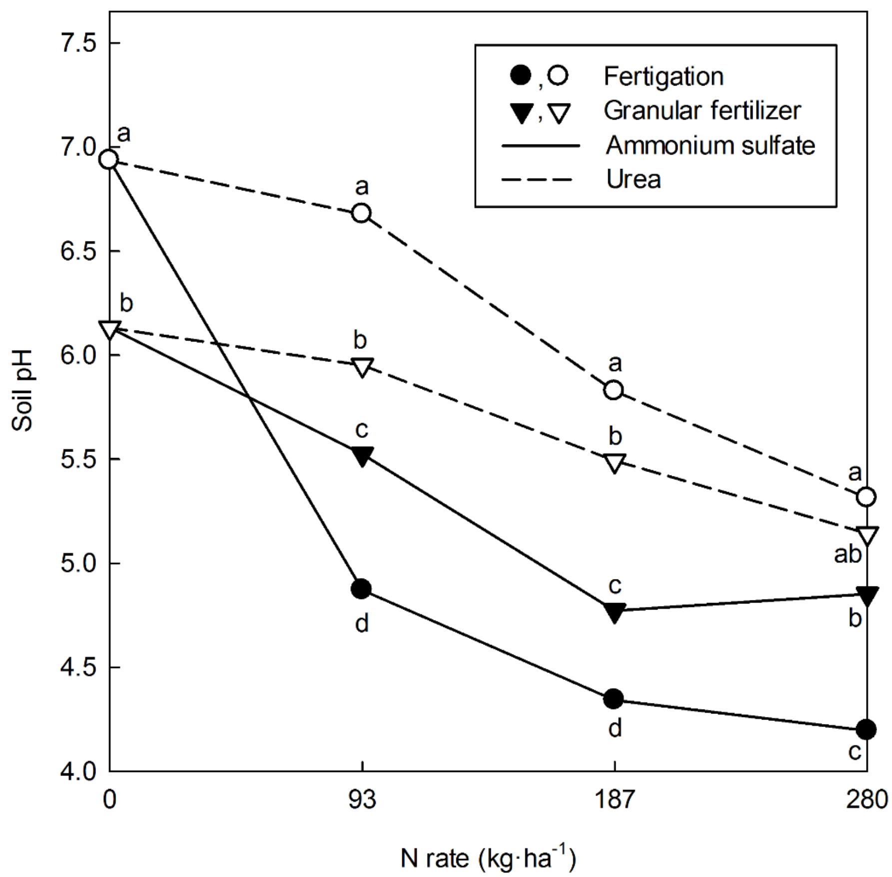

Figure 2-3 Soil pH at a depth of 0–20 cm in a field of 'Bluecrop' blueberry during the fifth year of fruit production (2012) in Oregon. Plants were non-fertilized or fertilized with three rates of ammonium sulfate or urea applied by fertigation or as granular fertilizer each year. Each symbol represents the mean of six replicates. Means with the same letter within each N rate are not significantly different, according to Tukey's HSD *test (*P *≤ 0.05).*

Chapter 3 – Root production and root lifespan in highbush blueberry in response to nitrogen fertigation and granular fertilizer

Oscar L. Vargas, Luis R. Valenzuela-Estrada, and David R. Bryla

Abstract

The effect of nitrogen (N) fertilizer applied through the drip irrigation system or as granular product was evaluated for impacts on fine root production and root lifespan using the minirhizotron technique in ‘Bluecrop’ highbush blueberry (*Vaccinium corymbosum* L.). Root dynamics were assessed during three growing seasons (2009−2011), corresponding to year 4 to 6 after planting. Liquid urea was injected through two laterals of drip tubing (fertigated), with 2 $L \cdot h^{-1}$ in-line emitters spaced every 0.3 m, situated one on each side of the plant row at 0.3 m from the crown. Nitrogen was fertigated weekly in 12 to 15 equal applications from spring through early summer. Granular ammonium sulfate was split into three equal monthly portions from mid-April to mid-June in plants irrigated by microsprinklers. Nitrogen application rates increased as plants matured − 150, 167, and 187 $kg \cdot ha^{-1}$ N for years 2009, 2010, and 2011, respectively. Controls without N fertilizer applied were irrigated with drip or microsprinklers. Cumulative root production was 2.6 times greater with granular ammonium sulfate than all other treatments and was mostly affected at 0–10 cm of soil depth. Two major peaks of root production were found, the first in May (before fruit harvest) and the second in September (after harvest, before dormancy). Model covariates for root survivorship included treatment, soil depth, seasonal root production (cohort), and root order. Root lifespan was longest with urea fertigation (184 d), and was 1.5 to 2.2 times longer than with granular ammonium sulfate (124 d) and with the un-fertilized drip control (84 d). Median root lifespan with the microsprinkler control (149 d) was similar to the fertigation treatment. When

analyzing all treatments together, roots produced at 30–40 cm of soil depth had a lower risk of mortality than roots produced at 0–10, 10–20, or 20–30 cm of soil depth; whereas roots produced before harvest were shorter-lived than roots produced after harvest. However, analysis of each treatment individually showed that roots produced at 10–20 cm in plants with fertigation had increased mortality compared to those produced at 0–10 cm, while mortality increased above 30 cm compared to roots produced below 30 cm of soil depth with granular ammonium sulfate. Roots produced before and after harvest had no difference in mortality with fertigation, but had a marginal increase in mortality for roots produced during fertilization months compared to the after harvest months. Specific root length was lower with fertigation than with granular ammonium sulfate, and therefore higher biomass was invested per unit of root with fertigation. These results show that belowground growth differed with fertigation and granular fertilizer. Fertigation produced fewer roots that lived longer, were more costly (more C cost per unit of root length), but were more efficient than roots produced with granular fertilizer. Our results may help improve fertilization guidelines. Fertilizer nutrient application should target periods of high new root production (more active in water and nutrient uptake), not only for better plant growth, yield, and fruit quality, but also to increase resource storage for improved plant growth at the beginning of the next growing season.

Introduction

A better understanding of belowground plant development is necessary to carry out efficient fertilization practices and improve irrigation efficiency. Understanding what affects root production and longevity is important to minimize nutrient leaching and thus maximize fertilizer use efficiency (Eissenstat and Volder, 2005). The root system of plants is composed of individual roots of different ages whose function is to absorb water and nutrients. Root growth, architecture, and the capacity to relocate in favorable soil portions are highly affected by birth and death of its individual units (Eissenstat and Yanai, 1997; Pregitzer et al., 1993). Root construction and maintenance requires high amounts of energy, and thereby influence carbon allocation and mineral nutrient consumption; whereas, root death returns these resources to the soil (Jackson et al., 1997).

Ericoid species, including blueberry, are noted for having very fine, fibrous roots without root hairs. The blueberry root system is relatively shallow, preferring to remain in the upper soil profile (Eck, 1988). In Oregon, Bryla and Strik (2007) found that most roots of three different cultivars were located in the top 20–30 cm of the soil profile. Similarly, a survey of 55 blueberry fields in Oregon showed that root length was generally greater in the upper 15 cm than in the lower 15–30 cm depth, but root biomass was greater at 15–30 cm than in the upper 15 cm (Scagel and Yang, 2008). Spiers (1986) observed that mulching tended to concentrate roots in the upper 15 cm of soil and also resulted in more uniform root distribution. However, with drip irrigation most roots appear to remain near the drip line (Gough, 1980; Eck, 1988; Bryla and Strik, 2007; Vargas et al., 2015 in press). Most blueberry roots are highly branched, with the finest roots reaching only 0.02 mm in diameter (Valenzuela-Estrada et al., 2008) or about twice the thickness of a typical single-cell root hair (Barber, 1984). Blueberry has been shown to have low fertilizer requirements likely because plants evolved in areas with low soil nutrient levels, high organic matter content, and high moisture; salinity levels of 1.68-2.28 $dS \cdot m^{-1}$ measured in soil saturation extracts has decreased yield due to fertilizer application (Coville, 1910; Townsend, 1973). Because of this, blueberry could be considered sensitive to relatively low soil salinity levels (Maas and Grattan, 1999). However, it has been clearly demonstrated that growth and yield improve with fertilization programs when low and stable nutrient soil levels are maintained during the growing season (Bryla and Machado, 2011; Vargas and Bryla, 2015).

Root birth and mortality are affected by endogenous and exogenous factors. Endogenous factors include species, carbon allocation to roots, root morphology, root architecture and mycorrhizal colonization (Valenzuela-Estrada et al., 2008; Wells and Eissensstat, 2001). Similarly, exogenous factors include soil nutrient concentration, environmental conditions, cultural practices, and herbivory pressure (Anderson et al., 2003; Burton et al, 2000; Wells et al., 2002b). Abbot and Gough (1987) found that blueberry roots grow in a bimodal pattern throughout the year, with the first peak in early June and the second in September. More roots were produced when soil temperatures ranged from 7 to 20°C and was optimum at temperatures of 14 to 18°C, suggesting that root growth was not only controlled by carbohydrate availability, but also by soil temperature. Valenzuela-Estrada (2008) showed no effect of reproductive stage on root production patterns during the three years of his study, and that root production normally increased in stage II of berry development (before berries turned blue). This was concomitant with warmer soil conditions (May-July), regardless of reproductive effort. Similarly, Gough (1994) showed that blueberry growing under cold spring temperatures not only had delayed bloom, but also slower root development.

There is inconsistency in how soil N availability affects root lifespan in different fruit crops. This indicates that other factors such as, resource availability, root diameter, soil depth, date of birth, and morphology, are also affecting root lifespan (Eissentat and Yanai, 1997; McCormack and Guo, 2014). On the other hand, different fertilizer application systems affect N concentration and root growth across the soil profile, particularly in shallow soil portions. Banding fertilizers localizes nutrients to a linear fraction of the root zone, while drip fertigation produces partial soil volume and a bulb-shaped pattern (Bar-Yousef, 1999; Haynes, 1990; Robinson, 1994). Regardless of the application system, fluctuations in nutrient concentration will depend on fertilizer frequency. Fertigation provides the benefit of reducing the salinity hazard in the root zone due to higher application frequency and improved nutrient distribution in the root zone (Bar-Yousef, 1999; Bryla and Machado, 2011; Vargas and Bryla, 2015). Granular N fertilizer application has been shown to generate high nutrient concentration in solution (high electrical conductivity) and may produce nutrient toxicity or nutrient imbalances. As a result, plants are affected from osmotic adjustments which requires more energy consumption, and may reduce yield or lower fruit quality (Grattan and Grieve, 1999; Bryla and Machado, 2011, Vargas and Bryla, 2015).

In blueberry (*Vaccinium corymbosum* L.), median root lifespan ranges from 115-120 d (Valenzuela-Estrada et al., 2008). Adams et al. (2013) found no change in lifespan in sassafras (*Sassafras Albidum*) and tulip tree (*Liriodendron tulipifera*) with N addition, but increased lifespan in 40-48% in white poplar (*Populus tremuloides*). Several studies have determined that fine diameter roots, which are the most active in absorbing water and nutrients, vary in lifespan, and may be replaced several times over the growing season (Eissenstat and Yanai, 1997, Volder et al., 2005), but also have high maintenance cost or shorter lifespan; whereas increasing soil depth normally decreases mortality (Anderson et al., 2003; Eissenstat and Volder, 2005). Nutrient uptake is normally positively correlated with the total root length for resource uptake, but the total length at any point in time is not only a result of root production, but also a result of cost and benefits from plants to keep roots alive (Adams et al., 2013; McCormack and Guo, 2014). Since root systems are not homogenous, the study of fine root dynamics needs to account for that variation (Baldi et al., 2010), particularly in crops with localized nutrient application.

Different ways to estimate root lifespan and morphology have been used in research studies, including monthly soil cores, N-balance approach, C-isotope approach, ingrowth cores, and direct observation (rhizotron and minirhizotron) (Madji et al., 2005). Although quite expensive, the use of minirhizotrons for direct observation has made the assessment of root demography more accurate (Eissenstat and Yanai, 1997). Direct observation avoids assumptions used in other methods in relation to interpretation, such as simultaneous birth and death during a sampling interval, or spatial and sampling variation being confounded with temporal variation. However, the problem associated with minirhizotrons and other direct observation approaches is the artificial environment at the surface of the observation window which may change root behavior (Eissenstat and Yanai, 1997; Harper et al., 1992). Cox proportional hazard regression is commonly used in minirhizotron studies to evaluate simultaneously the effect of these factors on mortality and survivorship (Allison, 2010; Cox, 1972; Wells and Eissenstat, 2001).

Nitrogen fertigation is beneficial over granular application on aboveground growth and yield in blueberry (Vargas and Bryla, 2015). However, the effect of these practices on belowground response has not been studied yet in blueberry. The objective of this study was to gain better understanding of blueberry root dynamics using two common N application systems in commercial fields, including granular ammonium sulfate and drip fertigation with urea. Factors affecting root production and mortality, root standing crop, and root lifespan were evaluated in a blueberry field over 3 years. In addition, root cores (taken only in the second year) were also used to identify effects of N application system on root morphology and thus, identify differences on biomass investment on root construction.

Materials and Methods

Study site. The study was conducted from 2009 to 2011 in a planting of ‘Bluecrop’ northern highbush blueberry (*Vaccinium corymbosum* L.) established in April 2006 at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, Oregon. Soil at the site was a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerols) with 2.4% organic matter content and initial pH of 6.2 (Nov. 2005). Two applications of 670 $kg \cdot ha^{-1}$ of elemental sulfur were incorporated into the field at 6 and 10 months each prior to planting, which reduced soil pH to 5.5 before establishment (Horneck et al., 2004). The plants were obtained from a commercial nursery (Fall Creek Farm & Nursery, Jasper, OR) as 18-month-old container stock and transplanted onto 0.4-m high × 0.9-m wide raised planting beds at an in-row spacing of 0.76 m. The raised beds were formed using a tractor-powered bed shaper and centered 3.0 m apart. A 7.5-cm deep × 1-m wide layer of Douglas-fir (*Pseudotsuga menziesii* Franco) sawdust was spread and rototilled into each row prior to shaping the beds (to increase soil organic matter content and improve drainage in the beds), and a 9-cm layer of sawdust was applied as mulch on top of beds immediately after planting (primarily for weed control). The sawdust mulch was reapplied every 2 years. Grass alleyways (1.5-m wide) were planted between the beds and mowed every 1 to 2 weeks during the growing season. Weeds were controlled, as needed, with glyphosate herbicide at the base of beds and hand-weeding on the top of beds. No insecticides or fungicides were applied during the study.

Experimental design and minirhizotron installation. An irrigation system was installed prior to planting and was designed with a manifold to accommodate 16 different fertilizer treatments. The treatments were arranged in a split-plot design with a combination of two N sources (ammonium sulfate and urea) and two methods of fertilizer application (dry granular applications and weekly fertigation) as main plots and four N rates as subplots. Each subplot consisted of one row of eight plants and was replicated six times. The planting contained a total of 952 plants and included 12 rows of treatment plots, with two border plants on each end, and two border rows on each side of the planting. Only four treatments and four blocks were used to study root dynamics using the minirhizotron technique. Treatments included drip fertigation with liquid urea (20–0–0), a drip irrigated treatment with no N fertilizer applied (drip control), a granular ammonium sulfate (21–0–0) coupled with microsprinkler irrigation, and an unfertilized treatment with microsprinkler irrigation (microsprinkler control).

Granular ammonium sulfate was applied by hand, once a month from April to June, in three equal portions per year. The fertilizers were spread along the row in a uniform, 20-cm-wide band concentrated at a distance of ≈0.3 m from each side of the plants (simulated applications by a fertilizer spreader). The fertilizer was immediately washed into the soil after application using 22.7 $L \cdot h^{-1}$ hanging fan-jet microsprinklers (DC Series, Bowsmith, Exeter, CA). The microsprinklers were attached to a trellis wire (suspended in the middle of the row at a height of 1.5 m) and were located directly between each plant in the treatment plot (i.e., six microsprinklers per plot). The system was operated at a pressure of 100-140 kPa, and each microsprinkler produced a circular-wetting pattern that was ≈2.3-m in diameter. Liquid urea was applied by fertigation. There were two lines of drip tubing (GeoFlow, Charlotte, NC) per row, one on each side of the plant and placed at a distance of ≈0.3 m. The lines had 1.9 $L \cdot h^{-1}$ integrated pressure-compensating emitters located every 0.30-m and were covered with sawdust mulch after installation. Liquid fertilizers were injected at the manifold using Venturi-type injectors (Mazzei Model 584 Injector Corp., Bakersfield, CA). Plants were fertigated weekly, beginning in mid-April each year and continuing until early-August. Fertigation was not applied throughout the entire growing season (i.e., April to September) because N applications in late summer may reduce flower bud set in blueberry and increase the potential for freeze damage over the winter (Hart et al., 2006). Fertilizers for both treatments, granular ammonium sulfate and fertigation with urea, were applied at total rates of 150 $kg \cdot ha^{-1}$ N in 2009, 167 $kg \cdot ha^{-1}$ N in 2010, and 187 $kg \cdot ha^{-1}$ N in 2011.

Plants were irrigated from mid-May or mid-June to late September depending on the year, with irrigation scheduled three to seven times per week based on daily estimates of crop evapotranspiration (Bryla, 2011) and monitored using water meters (Model SRII; Sensus, Raleigh, NC) installed at the inflow of each treatment. Due to lower efficiency, irrigation with microsprinklers required ≈40% more water than drip irrigation (Bryla, 2011). Since fertilizer application each year started in mid-April, before irrigation was needed, a small application of water was required for either fertilizer injection or granular incorporation. Similarly, controls without N received only water in the same amounts, beginning in mid-April.

In winter 2009, thirty two clear butyrate tubes (minirhizotrons) were installed near 16 plants at a distance of 0.3 m from the center of the plant crown; one plant was randomly chosen per treatment plot. Tubes were 0.90-m long and 5.7 cm external diameter and installed on each side of the plant (east and west) at an angle of 30° from the vertical, and inclined either to the left or right when facing the planting bed. Tubes were sealed at the bottom with acrylic cups and portions above the soil surface (≈15 cm) were wrapped with black electrical tape, and capped with black rubber stoppers to avoid moisture and light penetration. White PVC caps were also placed on the tube end to avoid radiation and heat exchange.

Root image capture and processing. Beginning in spring 2009, minirhizotron images were taken using a digital image capture system, Bartz camera equipped with I-CAP version 4.01 imaging software (Bartz Technology, Carpinteria, CA) connected to a computer. A total of 44 images (0.8 × 1.2 cm) were collected per tube, with the observation column oriented toward the plant. Images were taken approximately every 2 weeks from early-spring to early-fall, and approximately every 4 weeks from mid-fall to winter. Root data were processed using WinRHIZO Tron MF software (Regent Instruments, Quebec, Canada). Individual roots that grew against the observation windows were followed over three growing seasons, finishing in December 2011. Data consisted of date of birth (date in which an individual root was first observed, corresponding to the half date between root collection dates); date of death (date in which the root disappeared, corresponding to the half date between root collection dates); soil depth in centimeters (soil depth at which the root was found); root diameter in millimeters (measured to a nearest tenth of a millimeter on the first date that the root was observed); and root order [position in the branching system according to the number of visible laterals as described by Valenzuela-Estrada et al., (2008)].

Fine root production, root standing crop and root lifespan. New root production and mortality are events that occur simultaneously in the root system over the growing season. Thus, cumulative root production is different from root standing crop; the latter accounts only for the number of roots remaining alive at different times of the year. Root lifespan, in days, was calculated as the death date minus the birth date and was reported as the median number of days by which 50% of the roots were dead in a period of time. Because a large proportion of roots remained alive by the end of the study period, median lifespan is a better estimator and commonly used in survival analysis. Consequently, calculating the true mean is not advisable because it would overestimate the lifetime of a root or a cohort of roots (Madji et al., 2005).

Root cores. In July 2010, roots were sampled from each plot. A 38-cm long × 3.175-cm diameter soil probe (PN013, JMC 18” Large Diameter, Clements Associates Inc., Newton, IA) was used to collect root core samples to a depth of 0–30 cm. Samples were split into three portions of 0–10, 10–20, and 20–30 cm. Plots were sampled on each side of the planting bed, at a location directly between two plants, and ≈30 cm from the center of the row (i.e., where the fertilizer was banded applied in the granular plots and directly near a drip emitter in the fertigated plots). Roots were washed free of any soil in running tap water and extracted carefully with tweezers and stored in 50% ethanol and 50% DI water solution. Root length and diameter were measured using a flatbed scanner (1200 dpi resolution, 19-μm pixel size, 256-level grayscale, TIFF format; Epson Scanner Perfection 4490, USA) and Winrhizo software (Regent Instruments, Quebec, Canada). The scanned roots were classified based on root diameter, roots from 0-0.065 mm, 0.066-0.1 mm, and roots >0.1 mm in diameter (Valenzuela-Estrada et al, 2008).

After scanning, roots were dried at 70°C until a constant weight. Mass of dried roots was used to determine specific root length (SRL) and root tissue density (RTD). Root length density (RLD) and root diameter were also calculated from fresh root tissue. Root length density, specific root length, root tissue density, and root diameter reported in this work were based only on roots corresponding to diameters 0–0.065 mm, since roots in blueberry with higher absorptive capacities are within such a small root diameter (see Valenzuela-Estrada et al, 2008).

Data analysis. Root production and root standing crop from minirhizotron data, as well as root core data, were analyzed by analysis of variance (ANOVA) using the PROC MIXED procedure in SAS (Version 9.3 software, SAS Institute, Cary, NC). The model was fit for a split-plot design with four replicates, with application treatment and soil depth as factors. Means were separated at the 0.05 level using the Tukey-Kramer Honestly Significant Difference (HSD) test.

Cox proportional hazard regression was performed using the PROC PHREG procedure in SAS (Version 9.3 software, SAS Institute, Cary, NC) to identify significant variables (covariates) influencing root lifespan and mortality. Covariates used in the model were soil depth, root order, and date of birth (cohort), and were assigned categorical values prior analysis (Allison, 2010). Thus, roots were assigned one of four depth classes: 1, 2, 3, or 4 for roots produced at 0–10, 10–20, 20–30, or 30–40 cm of soil depth, respectively, while root order was assigned 1 or 2 (see Materials and Methods). Date of birth corresponded to periods of time when root production increased sharply over the season (periods of particular interest in this study). Thus, cohort was assigned one of three classes: 0, 1, or 2; “0” for no peak (late-fall to winter), “1” for the first peak (late-spring to early-summer), and “2” for the second peak (mid-summer to mid-fall). Even though root diameter was measured from minirhizotron images, it was not included in the hazard model due to a lack of a significant effect.

Cox proportional hazard regression analysis is based on the “hazard” ratio of a covariate (Cox, 1972). The hazard ratio represents the instantaneous probability of mortality on an individual root, although is not strictly a probability since can have values greater than 1 (Allison, 2010). The Cox’s partial likelihood method reports a parameter estimate (β) for each covariate or comparison in the case of categorical variables, and calculates a χ^2 statistic to test the null hypothesis that each β is zero. Increase or decrease in mortality depends on the sign of β and the significance of the P-value (i.e. < 0.05) for each χ^2 statistic calculated for each covariate (Allison, 2010; Wells and Eissenstat, 2001). A negative or positive β indicates a decrease or increase in mortality, respectively, and the proportion of change is given by a hazard ratio. Similar to orthogonal contrasts, hazard ratio for categorical covariates (as assigned in this study) can be interpreted as the calculated hazard for roots of value 1 vs. roots of value 2. For example, if the P-value < 0.05, $\beta > 0$, and the hazard a ratio equals to 1.5 for comparison of roots produced at soil depths of 20–30 cm vs. 10–20 cm, there is 50% higher mortality for roots produced at 20–30 cm compared roots produced at 10–20 cm of soil depth.

Results

Fine root production and root standing crop. The total number of roots found during the three years of study (2009–2011) was 2041, and the total number of roots per treatment was 505, 519, 261 and 756 in the drip control, microsprinkler control, fertigation with urea, and granular ammonium sulfate treatments, respectively.

Total fine roots produced was significantly affected by N application system (Table 3-1) in 2010, and in the cumulative analysis (2009–2011). Fine root production was similar between plants in control systems (without N). In addition, the total number of roots was 2.6–2.8 times greater with granular ammonium sulfate than with fertigation with urea. The percentage of roots that remained alive in each year (root standing crop) tended to be higher with fertigation in 2010 and 2011 and also in the cumulative analysis. Interestingly, root standing crop in 2010 and 2011 was almost 30% higher with fertigation than with granular fertilizer (Table 3-2, Figure 3-3).

Analysis at each soil depth showed that N application system significantly affected the number of roots produced mostly at 0–10 cm (

Table 3-3). Although the number of roots produced in plants fertilized with granular ammonium sulfate was four times greater (at 0–10 cm) than the number of roots in plants fertigated with urea in 2010, the difference was not significant. However, granular ammonium sulfate application significantly increased the number of roots compared to plants with only water applied by drip. In the same year, similar number of roots was found among plants fertigated with urea and the control plants (drip and microsprinkler). In 2011, the number of roots produced with granular ammonium sulfate application was the highest and was 2.6 times greater than in plants fertigated with urea. However, no difference was observed between control treatments, or between fertigation and the microsprinkler control. Similarly, the cumulative analysis showed the highest number of roots in plants when granular ammonium sulfate was applied and was, on average, 3.5 times greater than plants fertigated with urea or the controls (

Table 3-3). Treatment had a significant effect at the 10–20 cm depth only in 2009; plants in the microsprinkler control produced more roots than plants in the drip control or in the fertigation treatment, however, no difference was found among plants fertilized with granular ammonium sulfate, fertigated with urea, or when only water was applied by drip.

Cumulative root production at different depths is shown in Figure 3-1. In general, and accounting for all the treatments, 32%, 27%, 23%, and 18% of the roots were produced 0–10, 10–20, 20–30, and 30–40 cm of soil depth, respectively (

Table 3-3, Figure 3-1). Root production was significantly affected by treatment only at the 0–10 cm of soil depth during the entire length of the study and the number of roots was higher with granular ammonium sulfate than any other treatment. Fewer roots were produced with fertigation than with granular application and despite being significant only at 0–10 cm, fertigation showed a clear trend in which root proliferation decreased with increasing depths, being particularly low at 30–40 cm. On the other hand, the number of roots produced among control treatments was similar at each depth.

Effect of N application method on root lifespan. Cox proportional hazard regression revealed that treatment, soil depth, and time of birth (cohort) significantly affected root survivorship for the duration of the study (2009–2011; Table 3-4). Nitrogen application through either, fertigation or granular method, increased root lifespan by 1.5 to 2.2 times compared to drip control (

Figure 3-2). Plants fertigated with urea had the longest-lived roots, while plants receiving only water by drip had the shortest lived-roots. Root lifespan was 56 d longer in fertigated plants (184 d) compared to plants receiving granular fertilizer (126 d) (

Figure 3-2). Hazard ratios showed that roots from plants fertilized with granular ammonium sulfate had a 21% increase in mortality compared to roots from fertigated plants. Similarly, the risk of root mortality in control treatments decreased by 24% in plants receiving only irrigation by microsprinklers compared to plants receiving only irrigation by drip (Table 3-4). Root lifespan was 149 d and 84 d, respectively.

Effect of soil depth on root lifespan. Root mortality was similar among the three upper soil layers. Nonetheless, mortality risk was significant between roots produced at above and below the 30 cm of soil depth. There was, on average, 30% reduced mortality for roots produced at 30–40 cm compared to 0–10, 10–20, and 20–30 cm of soil depth (Table 3-4).

Root lifespan through the season. Time of root birth was included as a covariate to evaluate root longevity different in periods of the year (Figure 3-3; Figure 3-4). Roots produced from spring to early-summer (before harvest) had the shortest lifespan (Figure 3-5) and had a 18% to 32% increase in mortality compared to roots produced in late-summer to early-fall or in mid-fall to winter. No difference in mortality was observed during periods after harvest (Table 3-4).

Seasonal patterns of root production. The application of N fertilizer produced seasonal patterns of root production during the 3 years of study. Root production increased before and after fruit harvest (plants were harvested from mid-July through early-August in each year). However, only the increase in root production after harvest was observed during year in which the minirhizotron tubes were installed (winter 2009). In each year, the seasonal increase in root production was higher in plants fertilized with granular ammonium sulfate than plants fertigated with urea. Interestingly, no clear pattern was observed in control treatments (data not shown). In 2010 and 2011, two major peaks of root production were found (Figure 3-3; Figure 3-4). The first peak occurred between May and July, with the highest point of production in early-May for the fertigation treatment, and in late-May for the granular treatment. A rapid decline in root production occurred during fruit harvest, whereas, the second peak began the second (2009, 2010) or third (2011) week of August. The highest number of roots in the second peak of root production occurred early-September (2009), or mid- to late- September (2010, 2011) As observed in the first peak of production, root formation declined rapidly following maximum root numbers recoreded. In addition, a small increase also occurred early November in 2010, however the number was only about one third as what was measured in the major peaks earlier in the season. All periods of increase in root production were included in the hazard model.

Soil temperature was obtained from the local Pacific Northwest Cooperative Agricultural Weather Network AgriMet weather station (http://usbr.gov/pn/agrimet) located near the study site. Soil temperature was very similar among different depths (5, 10, and 20 cm), and revealed that the average soil temperature was 14-15°C when the first peak of root production started (May), and was 18-20°C at the maximum number of roots recorded for this peak (early-July). Whereas, average soil temperature was 19-22°C at the maximum number of roots recorded for the second peak (September). Soil temperature reached 23-25°C between peaks of root production (late-July, early-August) and were the periods of highest soil temperature during the year.

Effect of root order on root lifespan. No significant effect of root order on root mortality was observed.

Analysis for each treatment individually. Root mortality was not affected by year when included as a covariate in the Hazard regression analysis ($P > 0.05$). Therefore, individual analysis of treatments was performed for the duration of the study (2009–2011).

Drip and microsprinkler control treatments. In the un-fertilized controls, root mortality was affected by soil depth when drip irrigated, whereas root mortality was affected by time of birth (cohort) in the microsprinkler irrigated control (Table 3-5). Plants in the drip control had a decreased risk of root death (by 27% to 58%) as soil depth increased. In the microsprinkler control roots produced before harvest had lower life expectancy than roots produced after harvest. Thus, roots produced from spring to early-summer (before harvest) had, on average, 46% greater risk of mortality compared to those produced in late-summer to winter.

Fertigation and granular fertilizer treatments. Soil depth and cohort significantly affected root mortality when N was applied through fertigation. In contrast, only soil depth affected root mortality when granular N was applied, and the cohort effect had a marginal effect on root mortality (P = 0.0528, data not shown) (Table 3-5). In addition, roots from fertigated plants produced at 10–20 cm of soil depth had 78% higher mortality compared to those produced at 0–10 cm depth, but mortality decreased 34% to 62% for roots produced 20–30 and 30–40 cm depth, respectively, compared to at the 10–20 cm depth. In contrast, when granular ammonium sulfate was applied, there was no difference in root mortality within the first 30 cm of soil depth, but mortality decreased below 30 cm. Thus, mortality increased ≈60% for roots produced in the first 30 cm compared to roots produced below 30 cm. With fertigation, roots produced during spring to early-summer and mid-summer to late-fall (periods before and after harvest) had ≈ 3 times higher risk of mortality than those produced late-fall to winter. Although it was only a marginal main effect (P = 0.0528) with granular fertilizer, roots produced early in the season (or before harvest) had a 21% increase in mortality compared to those produced late in the season (or after harvest) (P = 0.0432 for the contrast). This shows that granular fertilization, which is applied from mid-April to mid-June resulted in a 21% increase of mortality in roots produced during the fertilization period compared to roots produced later in the season. Fertigation, on the other hand, only showed higher mortality over winter compared to the rest of the year.

Root morphology. Treatment had a significant effect on specific root length (cm root·mg^{-1} root) across all depths as well as at each depth (Table 3-6). Across all depths, specific root length was lowest in plants with fertigation and, therefore, the greatest biomass investment for construction of 1 cm of root. Specific root length was highest in control treatments and intermediate with granular ammonium sulfate. In 2010 and the cumulative analysis (Table 3-1), fertigation decreased the number of roots produced compared to granular ammonium sulfate, but at higher cost of biomass per unit of root produced (due to the lower specific root length). Similarly, limited soil N concentration (controls) increased specific root length and thus, biomass cost per unit of root constructed decreased. Nitrogen fertilization decreased specific root length but was statistically similar between N treatments. Root tissue density (mg root·cm^{-3} root) increased with granular fertilizer compared to the microsprinkler control and was similar to the fertigation treatment at the 0-10 and 10-20 cm depth. Consequently, higher root tissue density in N treatments showed higher amount of structural material invested by unit volume. Interaction between treatment and depth was observed only for root length density (cm root·cm^{-3} soil); treatments were different only at 10–20 cm, with ≈2 times greater root length density with fertigation than with granular ammonium sulfate. Therefore, fertigation produced roots with larger absorptive surface area at 10–20 cm than the granular treatment.

Discussion

Fine root production and root standing crop. Fertigation showed a significant decrease in the cumulative number of roots compared to granular ammonium sulfate at 0-10 cm of soil depth. However, with fertigation roots also had the capability to remain alive longer (longer lifespan) than with granular fertilizer. There was also a trend of higher root standing crop with fertigation compared to granular application. This was likely due to improved root environment provided with fertigation. Bryla and Machado (2011) showed better plant growth in young blueberry plants with N fertigation than with granular N, the result was linked to lower NO_3-N and NH_4-N concentration in the root zone with weekly fertigation. Ammonium N assimilation occurs in the roots and requires carbohydrates (energy). Any shortage of energy in the root with high soil NH_4-N concentration may cause ammonia accumulation in the cytoplasm of root cells and root death. Salinity stress, similar to high root temperatures (Ganmore-Newman and Kafkafi, 1983), might reduce sugar content in the root due to increased respiration and therefore increased root sensitivity to NH_4-N (Bernstain and Kafkafi, 2002).

In this study, root production was mostly affected in the first 10 cm of the soil profile. Granular fertilizer increased the number of roots compered to fertigation or the unfertilized controls. Granular fertilizer applied in a triple split over the spring has been demonstrated to increase soil solution electrical conductivity to 8-13 $dS \cdot m^{-1}$, which is on average, 5-fold higher than the level considered safe for salt-sensitive crops such as blueberry (< 2 $dS \cdot m^{-1}$) (Bryla and Machado, 2011; Maas and Grattan, 1999). Weekly fertigation, while providing the same amount of N over the growing season, maintained salinity levels below that threshold (Bryla and Machado, 2011). This was later corroborated by Vargas and Bryla (2015) who showed better plant growth and yield with fertigation. Harper et al. (1991) suggest that increase in fine root production does not add benefit over root extension with proper soil environment and nutrients (i.e. with fertigation). This agrees with our result in which more roots were produced with granular fertilizer, but root length density was lower in the upper 20 cm of the soil profile (measured in 2010). Excess of nutrients (high salinity) decreases soil osmotic potential and may damage root apical meristems, reduce root elongation, and increase in root proliferation (Bernstein and Kafkaki, 2002; Kramer, 1980). Similarly, Friend et al., (1990) showed that root proliferation of Douglas-fir seedlings increased 2.3 times in high N availability compared to low N availability.

The number of roots produced had two major peaks during the growing season, in May (before harvest) and September (after harvest). Similarly, Valenzuela-Estrada et al. (2008) reported that root production normally increased in May-July in stage II of berry development (before berries change from green to blue). In this study, the maximum number of roots recorded during the growing season coincided with high soil temperature throughout the year (18-22°C); however, the highest soil temperature occurred between peaks of root production (23-25°C). Abbot and Gough (1987) showed also two peaks of root growth in blueberry and found that root growth was rapid before fruit maturity (early-June), declined during harvest (mid-July), and was greatest in flower bud formation (early-September). They also suggest that root growth was correlated to soil temperature, shoot growth and phenolical stage. However, optimum temperature for root growth was lower than our findings. They found highest root growth at 14-18°C of soil temperature and that declined outside that range. In general, it has been reported that root growth in fruit crops shows seasonal periodicity and can be affected by fruit sink (Atkinson, 1980), and most studies have reported peaks of root growth in the spring and summer after harvest.

Root lifespan. Roots with the ability to live longer with fertigation is one of the most interesting results from this research. Our results show that the overall lifespan across all covariates in blueberry was 117 d. Median root lifespan was 1.5 to 2.2 times longer with fertigation (184 d) than with only water applied by drip (84 d) or with granular fertilizer (124 d). Valenzuela-Estrada et al., (2008) found that root lifespan of blueberry raged from 115 to 120 d for first and second order roots with application of ≈ 70 $kg{\cdot}ha^{-1}$ of N as granular fertilizer. The importance of longer lifespan has been reported in many studies. Root lifespan is often associated to benefits of nutrient uptake versus carbon costs to maintain roots alive; thus, the advantage of longer lifespan depend on the relative pay-off of carbon invested on root maintenance (Esissenstat and Yenay, 1997). Nitrogen assimilation requires high rates of protein turnover (Bouma et al., 1996). Therefore, nutrients are also considered the currency for cost-benefit assessment of root lifespan (Adams et al., 2013; Eissenstat and Yenay, 1997). Adams et al. (2013) found 40% to 45% longer root lifespan with N fertilization in two fine root tree species, *Popolus tremuloides* Michx and *Acer Negundo* L., with 69 vs 102 d and 113 to 188 d, respectively. Similarly, localized N application increased root lifespan and root length in forest tress compared the control with only water applied (Pregistzer et al., 1993). Conversely, Bai et al. (2008) found lower root survivorship with N application in grass (*Leymus chinensis*) for roots produced at 0–10 and 10–20 cm of soil depth compared to the control without N; however, N had no effect on root lifespan at 10–20 cm. In peach, Baldi et al. (2010) found longer lifespan with compost as N source, intermediate with conventional N fertilizer, and lower in the control without N. They suggest that longer lifespan may be due to improved chemical and physical soil properties provided by compost (i.e. higher buffer capacity).

Soil depth effect on root lifespan. Root mortality, across all treatments, decreased for roots produced at 30–40 cm compared to categories of roots produced above 30 cm. However, analysis of each treatment revealed differences among them, for example soil depth did not affect root mortality in the microsprinkler control and root mortality differed within the first 20 cm only with drip treatments (with or without N), and decreased at 10–20 cm compared to 0–10 cm in the drip control, but increased with fertigation at 10–20 cm compared to 0–10 cm of soil depth. This may be explained by the adequate soil NH_4-N concentration in the uppermost layer with fertigation in which blueberry plants prefer to maintain root production near emitters and extend their lifespan (Bryla and Machado, 2011; Eissenstat and Yanai, 1997; Haynes, 1990). When granular fertilizer was applied, root mortality increased above 30 cm of soil depth compared to roots produced below 30 cm of soil depth. Therefore, the triple split granular application may have caused excessive nutrient concentration in the first three uppermost soil layers resulting in increased root mortality, but also increased production of new roots. Consequently, NH_4-N in excess may produce toxicity or may be rapidly nitrified into NO_3-N, in both cases affect negatively the root system of blueberry plants. Townsend (1967) showed improved growth and healthier roots with NH_4-N supply than only NO_3-N. Roots receiving only NO_3-N were unhealthy and appeared as dark-brown or black. Later, Claussen and Lenz (1999) suggested that NH_4-N is essential for optimum blueberry growth due to lack of nitrate reductase activity in shoots and very low activity of this enzyme in roots that are unable to meet plant demands when NO_3-N is the primary N source. The effects of nutrient concentration on root mortality are difficult to assess in this study since soil solution N (and its different forms) was not evaluated; however, it is clear that drip fertigation and granular application (plants irrigated by microsprinklers), produce different wetting patterns (Haynes, 1990; Pelletier and Tan, 1993) in which roots develop and survive. Fertigation is well known to increase nutrient use efficiency compared to granular application (Bar-Yousef, 1999) and thus it is an advantage for plants to extend root lifespan in adequate soil conditions (Eissenstat and Yanai, 1997; Yanai et al, 1995).

Root lifespan through the season. In the duration of this study, root mortality was higher for roots produced in spring-early to summer (before harvest) than in early summer to fall (after harvest) or late-fall to winter (dormancy). However, the effect of date of birth on root mortality varied with treatments. Root mortality with fertigation was about three times higher for roots produced before and after harvest than late-fall to winter. However, the seasonality effect on root mortality was only marginal with granular fertilizer. With granular fertilizer, roots produced early in the season (or before harvest) had a 21% increase in mortality compared to those produced late in the season (or after harvest), while roots in fertigated plants showed no difference between those periods. This shows the relevance of weekly fertigation over a triple split granular application; while the former showed no effect on root mortality over the growing season, granular fertilizer tended to increase root mortality during the fertilization period (mid-April to mid-June) compared to periods of no fertilization (i.e. after harvest). Effects of seasonality have also been reported by other authors. Bai et al, (2008) found longer lifespan for grass roots (*Leymus chinensis*) produced in fall compared to roots produced in the spring. Similarly, Anderson et al. (2003) found that Concord grape roots produced near bloom were shorter-lived than roots produced later in the season. Root mortality due to time of birth may vary as a result of a number of factors, including moisture, temperature, and carbohydrate availability (Anderson. et al 2003; Baddeley and Watson, 2005). One of the most important factors on root longevity in perennial crops is carbon allocation. Roots produced early in the season have the primary function of absorbing water and nutrients for aboveground growth, while roots produced late in the summer and fall have also the function of storage before dormancy (Lopez et al., 2001). Thus, the increase on mortality for roots produced before harvest may be due to increased aboveground carbon allocation for shoot and fruit production.

Root morphology. Differences in root diameter between treatments were not significant across treatments. Specific root length with the fertigation treatment was the smallest across all depths in root cores. Specific root length was often lower with N addition than without it (Table 3-6). Therefore, N application, particularly when applied through fertigation, shifted pants into investing more biomass per unit of root produced. Root length density appeared to be higher at 10–20 cm with fertigation and drip control, and was on average two times higher than with granular fertilizer; therefore, drip treatments had larger absorptive area at that depth. On the other hand, root tissue density tended to increase with N addition across all depths. More dense roots have higher amount of biomass invested per unit of root volume. Eissenstat (1992) suggests that production of roots at high specific root length is associated with more root expansion. Vemerali et al. (2009) showed that root length density was higher at an intermediate N rate (90 $kg \cdot ha^{-1}$) in irrigated sugar beet but decreased with higher N application. More biomass invested in roots with nitrogen application, and particularly with fertigation, suggests that blueberry plants may shift carbon allocation not only into more efficient roots, but also into extending their lifespan (Yanai et al, 1995). In addition, more efficient roots are maintained longer in adequate soil condition since they provide more return (uptake) relative to the resources invested for root maintenance (Eissenstat, 1992; Eissenstat and Yanai, 1997).

Conclusions

In conclusion, this study shows that different N application systems have strong effect on root production and root lifespan of blueberry. Covariates included in this study showed that mortality of roots may have different effect on the whole blueberry system. In particular, fertigation clearly reduced the number of roots produced and increased root lifespan. The implications of fertigation over granular application relies on the capability of plants to produce more efficient roots in a low stress soil environment and, thus keep them alive for a longer time. This is translated into more aboveground production as shown as shown by Vargas and Bryla (2015). Specific root length was lower with fertigation than with granular application. Since new roots are more active in water and nutrient uptake, peaks of root production over the growing season provide benefits for best fertilization guidelines in blueberry. Proper N application should increase throughout the season as the number of roots increases until the first peak. In addition, peaks root of production may be a starting point for further research to evaluate the application of other nutrients since fertigation has the advantage and flexibility of applying soluble nutrients to match plant needs and in periods of high root activity.

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Tables and Figures

Table 3-1 Effect of N application system on total number of roots produced at 0-40 cm depth in 'Bluecrop' blueberry during three growing seasons (2009–2011).

	Number of roots per cm² of minirhizotron view area			
Treatment	2009	2010	2011	Cumulative
Drip control	0.55	0.74 ab[z]	0.58	1.88 ab
Fertigitation Urea	0.23	0.48 b	0.38	1.10 b
Microsprinkler control	0.84	0.79 ab	0.24	1.88 ab
Granular Amm. Sulfate	0.62	1.32 a	0.92	2.86 a
Signif.	0.1710	**0.0388**	0.119	**0.0291**

[z]Means (n = 4) followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey's HSD test. Data were log transformed prior analysis. Nitrogen rates were 150, 167, and 187 $kg \cdot ha^{-1}$ N in 2009, 2010, and 2011, respectively.

Table 3-2 Effect of N application system on root standing crop in 'Bluecrop' blueberry during three growing seasons (2009–2011). Values are expressed as percentage of roots remaining alive relative to the total number of roots produced at the end of each year.

	Root standing crop (%)			
Treatment	2009	2010	2011	Cumulative
Drip control	32[z]	30	46	33
Fertigitation Urea	55	65	63	58
Microsprinkler control	59	39	19	46
Granular Amm. Sulfate	76	41	30	44
Signif.	0.2344	0.2454	0.3547	0.4236

Percentages are mean of four replicates (n = 4).

Table 3-3 Effect of N application system on number of roots produced in 'Bluecrop' blueberry at different soil depths during three growing seasons (2009–2011).

		Number of roots per cm^2 of minirhizotron view area			
Treatment	Depth (cm)	2009	2010	2011	Cumulative
Drip control	0-10	1.15	0.41 b[z]	0.05 c	1.61 b
Fertigitation Urea	0-10	0.27	0.57 ab	0.63 b	1.46 b
Microsprinkler control	0-10	0.51	0.77 ab	0.24 bc	1.52 b
Granular Amm. Sulfate	0-10	1.40	2.29 a	1.63 a	5.32 a
Signif.		0.3638	**0.0409**	**0.0123**	**0.0093**
Drip control	10-20	0.27 b	0.89	0.32	1.47
Fertigitation Urea	10-20	0.14 b	0.76	0.43	1.33
Microsprinkler control	10-20	1.47 a	0.98	0.07	2.52
Granular Amm. Sulfate	10-20	0.57 ab	1.42	0.96	2.95
Signif.		**0.0293**	0.8038	0.1750	0.2423
Drip control	20-30	0.32	0.90	0.66	1.88
Fertigitation Urea	20-30	0.41	0.57	0.17	1.15
Microsprinkler control	20-30	0.96	0.74	0.57	2.27
Granular Amm. Sulfate	20-30	1.19	0.93	0.51	1.66
Signif.		0.1281	0.8038	0.1909	0.6117
Drip control	30-40	0.43	0.78	1.37	2.57
Fertigitation Urea	30-40	0.09	0.02	0.27	0.37
Microsprinkler control	30-40	0.46	0.69	0.05	1.21
Granular Amm. Sulfate	30-40	0.28	0.69	0.62	1.60
Signif.		0.4117	0.1328	0.2736	0.6117
	0-10	0.83	1.01 a	0.64	2.47 a
	10-20	0.61	1.01 a	0.44	2.07 ab
	20-30	0.47	0.79 a	0.48	1.74 ab
	30-40	0.32	0.55 b	0.58	1.43 b
Depth	Signif.	0.0969	**0.0130**	0.2780	**0.0069**
Treatment	Signif.	**0.0462**	**0.0164**	0.0956	**0.0376**
Treatment x depth	Signif.	0.6705	0.4874	**0.0007**	0.3972

[z]Means (n = 4) followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey's HSD test. Data were log transformed prior analysis.

Table 3-4 Results of proportional hazard regression analyses for individual root lifespan of 'Bluecrop' blueberry over a three year period (2009—2011).

		2009—2011				
Variable	df	Paremeter estimate	Standard error	χ2	*P*-value	Hazard ratio
Treatment						
Drip control vs. fertigation with urea	1	0.4428	0.0954	21.5604	**<0.0001**	**1.56**
Microsp. Control vs. fertigation with urea	1	0.1708	0.0945	3.2679	0.0706	1.19
Granular amm sulfate vs. fertigation with urea	1	0.1906	0.0895	3.1560	**0.0398**	**1.21**
Microsp. Control vs. drip control	1	-0.2721	0.0601	11.8926	**0.0006**	**0.76**
Granular amm sulf vs drip control	1	-0.2702	0.0570	13.0997	**0.0003**	**0.76**
Granular amm. Sulf vs microsp control	1	0.0018	0.0765	0.0006	0.9808	1.00
Depth						
10-20 cm vs. 0-10 cm	1	-0.0856	0.0737	1.3495	0.2454	0.92
20-30 cm vs 0-10 cm	1	-0.0506	0.0753	0.4513	0.5017	0.95
20-30 cm vs 10-20 cm	1	0.0350	0.0801	0.2049	0.6508	1.04
30-40 cm vs 0-10 cm	1	-0.4028	0.0865	21.7009	**<0.0001**	**0.67**
30-40 cm vs 10-20 cm	1	-0.3172	0.0643	12.9070	**0.0003**	**0.73**
30-40 cm vs 20-30 cm	1	-0.3523	0.0625	15.6835	**<0.0001**	**0.70**
Cohort						
Spring – early-summer vs. late-fall – winter	1	0.2777	0.1001	7.7004	**0.0055**	**1.32**
Mid-summer – mid-fall vs. late-fall – winter	1	0.1139	0.0957	1.4177	0.2338	1.12
Mid-summer – mid-fall vs. spring – early-summer	1	-0.1638	0.0506	7.5552	**0.0060**	**0.85**
Spring – early-summer vs. mid-summer – mid-fall	1	0.1638	0.0702	7.5552	**0.0060**	**1.18**
Order						
1 vs 2	1	0.1126	0.0724	2.4184	0.1199	1.12

Table 3-5 Results of proportional hazard regression analyses for individual root lifespan of 'Bluecrop' blueberry over a three year period (2009—2011). Each treatment was analyzed separately for the whole period of study (2009—2011).

	Drip control						Microsprinkler control					
	2009—2011						2009—2011					
Variable	df	Parameter estimate	Standard error	χ2	*P*-value	Hazard ratio	df	Parameter estimate	Standard error	χ2	*P*-value	Hazard ratio
Soil depth												
10-20 cm vs. 0-10 cm	1	-0.5465	0.1606	11.5768	**0.0007**	**0.58**	1	-0.2755	0.1695	2.6412	0.1041	0.76
20-30 cm vs 0-10 cm	1	-0.6484	0.1524	18.1052	**<.0001**	**0.52**	1	0.0310	0.1606	0.0372	0.8472	1.03
20-30 cm vs 10-20 cm	1	-0.1019	0.1492	0.3803	0.5374	0.90	1	0.3065	0.1866	4.9780	0.0257*	1.36
30-40 cm vs 0-10 cm	1	-0.8673	0.1506	33.1475	**<.0001**	**0.42**	1	-0.0147	0.2012	0.0054	0.9417	0.99
30-40 cm vs 10-20 cm	1	-0.3208	0.1149	4.1027	**0.0428**	**0.73**	1	0.2607	0.2312	2.1426	0.1433	1.30
30-40 cm vs 20-30 cm	1	-0.2189	0.1179	2.2256	0.1357	0.80	1	-0.0457	0.1671	0.0682	0.7939	0.96
Cohort												
Spring – early-summer vs. Late-fall – winter	1	0.1880	0.2148	0.7659	0.3815	1.21	1	0.3801	0.1615	5.5369	**0.0186**	1.46
Mid-summer – mid-fall vs. Late-fall – winter	1	0.1921	0.2001	0.9218	0.3370	1.21	1	0.0092	0.1537	0.0036	0.9522	1.01
Mid-summer – mid-fall vs. Spring – early-summer	1	0.0041	0.1277	0.0010	0.9742	1.00	1	-0.3709	0.0918	7.7802	**0.0053**	0.69
Spring – early-summer vs. Mid-summer – mid-fall	1	-0.0041	0.1267	0.0010	0.9742	1.00	1	0.3709	0.1927	7.7802	**0.0053**	1.45
Root order												
1 vs 2	1	0.1672	0.1291	1.6764	0.1954	1.18	1	-0.0414	0.1679	0.0608	0.8053	0.96

(*) not significant when main effect P-value is not significant (*P* > 0.05)

Table 3-5 Continued

	Fertigation with urea						Granular ammonium sulfate					
	2009—2011						2009—2011					
Variable	df	Parameter estimate	Standard error	χ2	*P*-value	Hazard ratio	df	Parameter estimate	Standard error	χ2	*P*-value	Hazard ratio
Soil depth												
10-20 cm vs. 0-10 cm	1	0.5759	0.1933	8.8746	**0.0029**	**1.78**	1	0.2199	0.1122	3.8386	0.0551	1.25
20-30 cm vs 0-10 cm	1	0.1532	0.1997	0.5885	0.4430	1.17	1	0.1135	0.1332	0.7259	0.3942	1.12
20-30 cm vs 10-20 cm	1	-0.4227	0.1360	4.1451	**0.0418**	**0.66**	1	-0.1065	0.1363	0.4932	0.4825	0.90
30-40 cm vs 0-10 cm	1	-0.3846	0.3816	1.0155	0.3136	0.68	1	-0.4017	0.1495	7.2211	**0.0072**	**0.67**
30-40 cm vs 10-20 cm	1	-0.9605	0.1476	6.2042	**0.0127**	**0.38**	1	-0.6216	0.0873	14.6112	**0.0001**	**0.54**
30-40 cm vs 20-30 cm	1	-0.5377	0.2322	1.8294	0.1762	0.58	1	-0.5152	0.1076	8.1813	**0.0042**	**0.60**
Cohort												
Spring – early-summer vs. Late-fall – winter	1	1.1387	0.4169	7.4626	**0.0063**	**3.12**	1	0.3919	0.2220	3.1169	0.0775	1.48
Mid-summer – mid-fall vs. Late-fall – winter	1	1.1054	0.4151	7.0904	**0.0077**	**3.02**	1	0.2042	0.2202	0.8602	0.3537	1.23
Mid-summer – mid-fall vs. Spring – early-summer	1	-0.0333	0.1577	0.0418	0.8380	0.97	1	-0.1877	0.0769	4.0892	0.0432*	0.83
Spring – early-summer vs. Mid-summer – mid-fall	1	0.0333	0.1686	0.0418	0.8380	1.03	1	0.1877	0.1120	4.0892	0.0432*	1.21
Root order												
1 vs 2	1	0.1532	0.2052	0.5573	0.4554	1.17	1	-0.1682	0.1432	1.3798	0.2401	0.85

(*) not significant when main effect P-value is not significant ($P > 0.05$)

Table 3-6 Root length density, specific root length, root tissue density, and root diameter of 'Bluecrop' blueberry measured at different soil depths. Roots were collected from root cores sampled in July 2010. Values represent the mean of 8 cores per treatment, two cores per plot in four blocks (n=4).

Soil depth	Treatment	Root length density (cm root/cm^3 soil)	Specific root length (cm root/mg root)	Root tissue density (mg root/cm^3 root)	Root diameter (mm)
0-10 cm	Drip control	13.3	47.7 ab[z]	2.49 ab	1.06
	Fertigation with urea	10.9	27.1 b	3.36 a	1.25
	Microsprinkler control	11.6	62.2 a	2.02 b	1.06
	Granular ammonium sulfate	7.1	34.2 b	3.09 a	1.18
	Significant	0.3742	**0.0006**	**0.0141**	0.3255
10-20 cm	Drip control	19.6 a	52.3 ab	2.49 ab	1.04
	Fertigation with urea	17.4 ab	30.5 c	3.08 ab	1.23
	Microsprinkler control	11.8 bc	59.0 a	2.20 b	1.04
	Granular ammonium sulfate	9.0 c	43.1 b	3.32 a	0.99
	Significant	**0.0014**	**0.0008**	**0.0236**	0.2613
20-30 cm	Drip control	13.6	41.2 ab	3.35	1.03
	Fertigation with urea	7.6	23.7 b	3.10	1.34
	Microsprinkler control	11.4	49.6 a	2.15	1.20
	Granular ammonium sulfate	16.2	38.9 ab	2.65	1.19
	Significant.	0.2387	**0.0138**	0.109	0.1669
0-10 cm		10.7	42.8 ab	2.74	1.14 ab
10-20 cm		14.5	46.2 a	2.77	1.07 b
20-30 cm		12.2	38.3 b	2.81	1.19 a
Significant		0.1178	**0.0353**	0.9177	**0.0122**
	Drip control	15.5	47.0 ab	2.78 ab	1.04
	Fertigation with urea	12	27.1 c	3.12 a	1.27
	Microsprinkler control	11.6	56.9 a	2.12 b	1.10
	Granular ammonium sulfate	10.8	38.7 b	3.02 ab	1.12
	Significant	0.0819	**0.0004**	**0.0215**	0.2454
	Treatment X Depth	**0.0356**	0.5732	0.0815	0.3000

[z]Means followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey's HSD test.

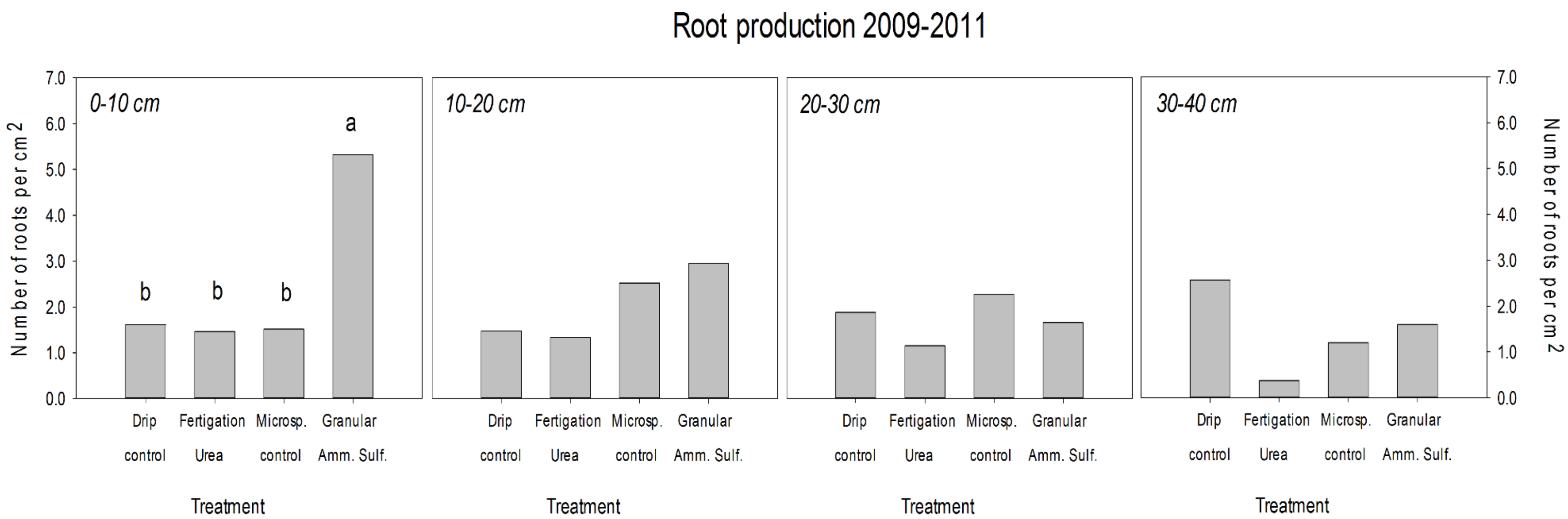

Figure 3-1 Cumulative fine root production of 'Bluecrop' blueberry at different soil depths over three growing seasons (2009—2011). Plants were irrigated through a drip system (only water; Drip control), fertigated through a drip system (Fertigation with urea at a rate of 150-187 kg·ha^{-1} N), irrigated though a microsprinklers system (only water; Microsprinkler control), or fertilized with granular fertilizer and irrigated through microsprinklers (Granular ammonium sulfate at a rate of 150-187 kg·ha^{-1} N). Values are average of four replications. Means among bars followed by a different letter are significantly different at $P \leq 0.05$*, according to Tukey's HSD test. Data were log transformed prior analysis and back transformed for presentation.*

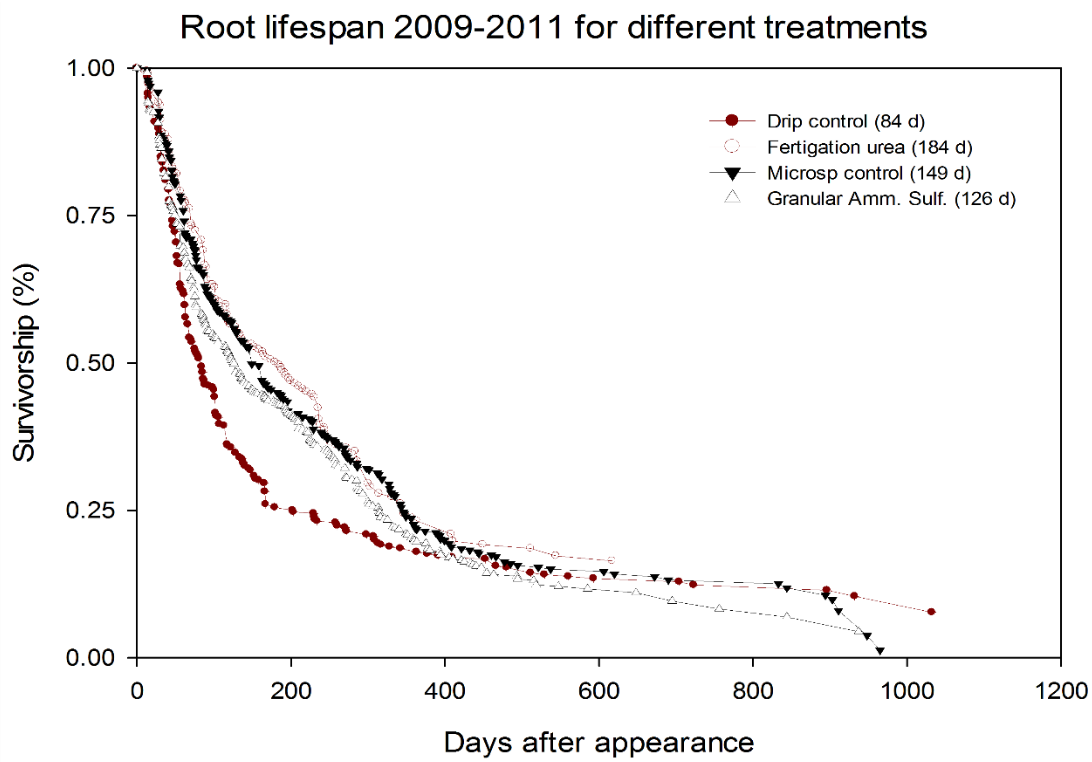

Figure 3-2 Treatment effect on the survival provability of 'Bluecrop' blueberry fine roots over a three year-period (2009—2011). Curves were generated using the BASELINE statement of PROC PHREG in SAS with treatment as stratifying variable. Median survivorship is determined as the time in days at which 50% of the roots die. Plants were irrigated through a drip or a microsprinkler system [only water; Drip control (●), Microsprinkler control (▼)], fertigated through a drip system [Fertigation with urea (○)], or fertilized with granular fertilizer and irrigated through microsprinklers [Granular ammonium sulfate; (△)]. Nitrogen rates were 150, 167, and 187 kg·ha^{-1} N in 2009, 2010, and 2011, respectively.

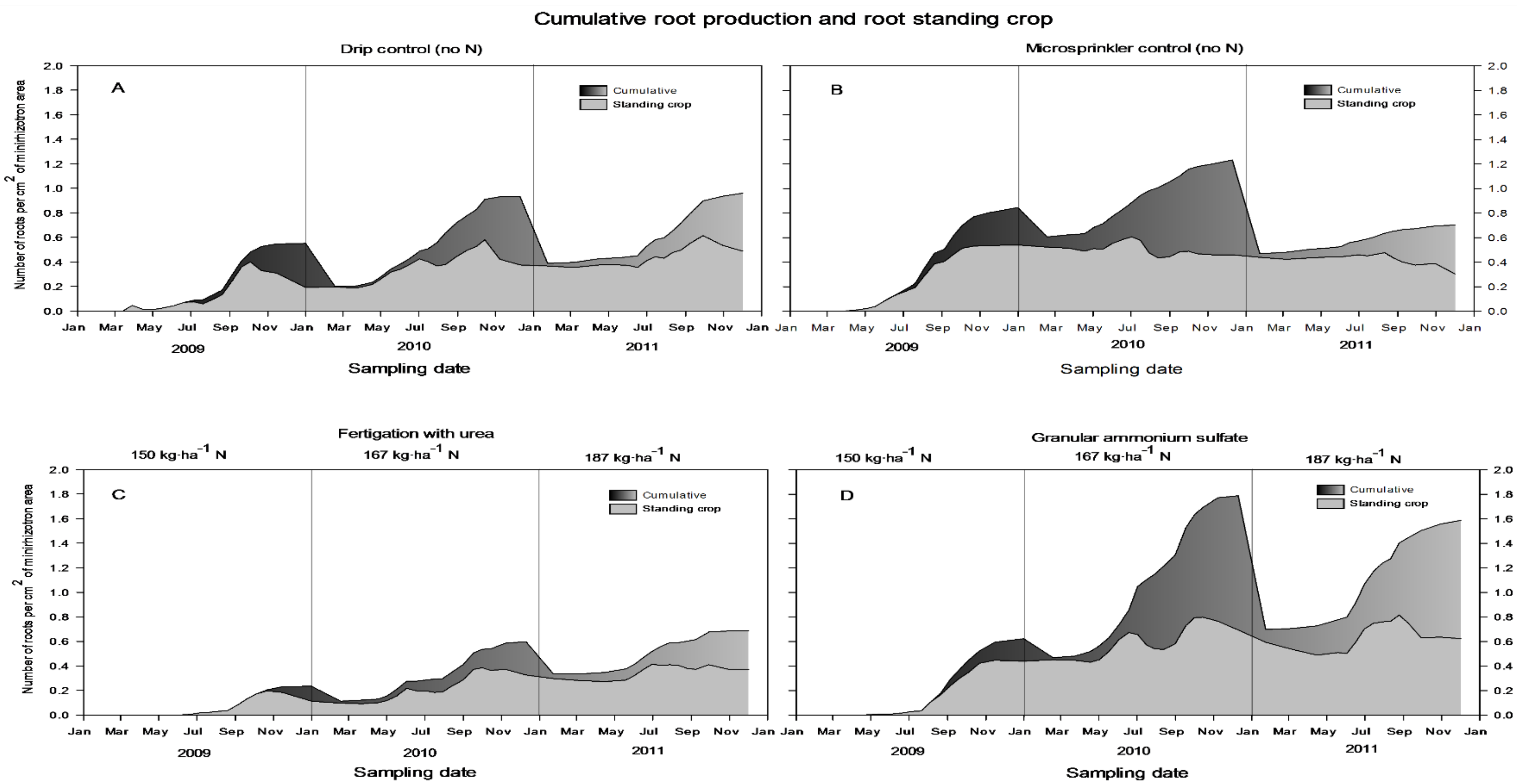

Figure 3-3 Cumulative root production and root standing crop for each sampling date during 2009-2011 seasons of highbush irrigated by drip (drip control; A), irrigated by microsprinklers (microsrprinkler control; B), fertilized with liquid urea (drip fertigation; C), and fertilized with granular ammonium sulfate (granular application; D). Data is expressed as the number of roots per square centimeter of minirhizotron view area. The number of roots found from the two tubes installed per plant were averaged. Lines represent the number of roots averaged from four replicates.

99

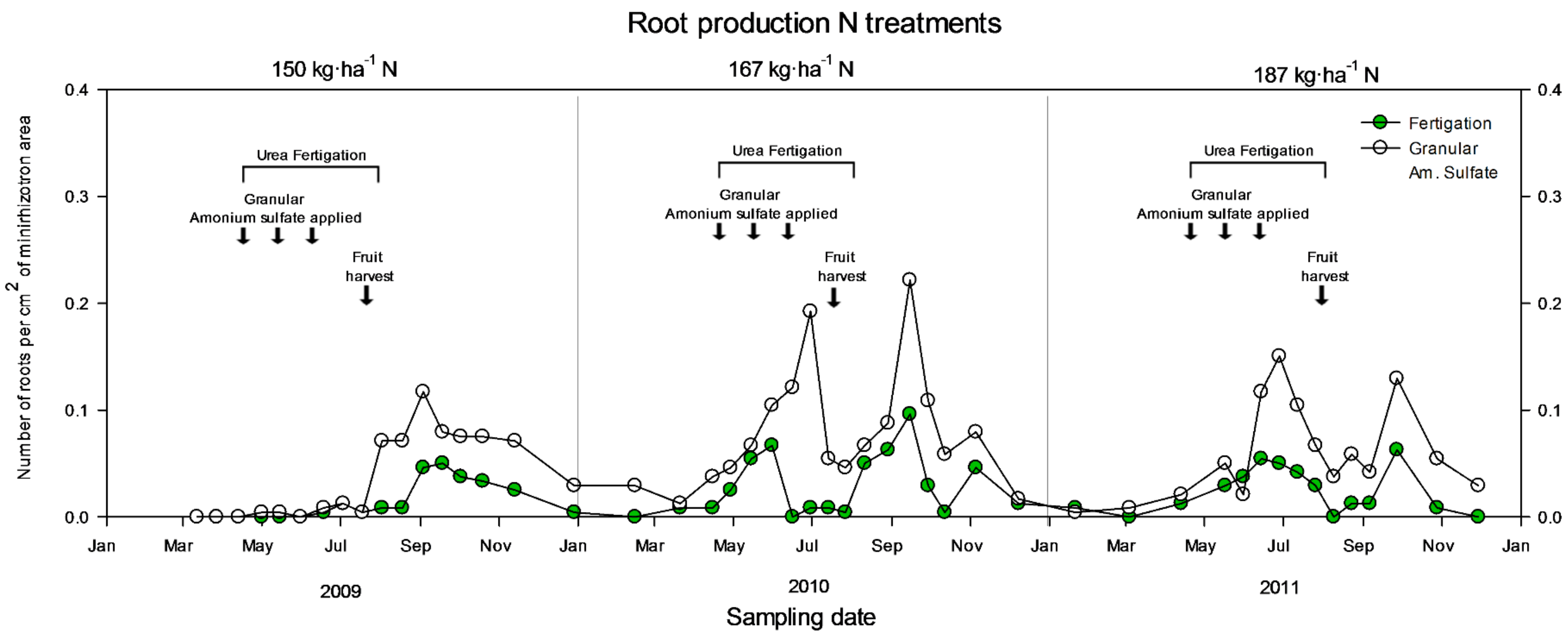

Figure 3-4 New fine root production for each sampling date during 2009-2011 seasons of highbush fertilized with liquid urea [drip fertigation (●)], or fertilized with granular fertilizer [granular ammonium sulfate (○)]. Data is expressed as the number of roots per square centimeter of minirhizotron view area. The number of roots found from the two tubes installed per plant were averaged. Lines represent the number of roots averaged from four replicates.

100

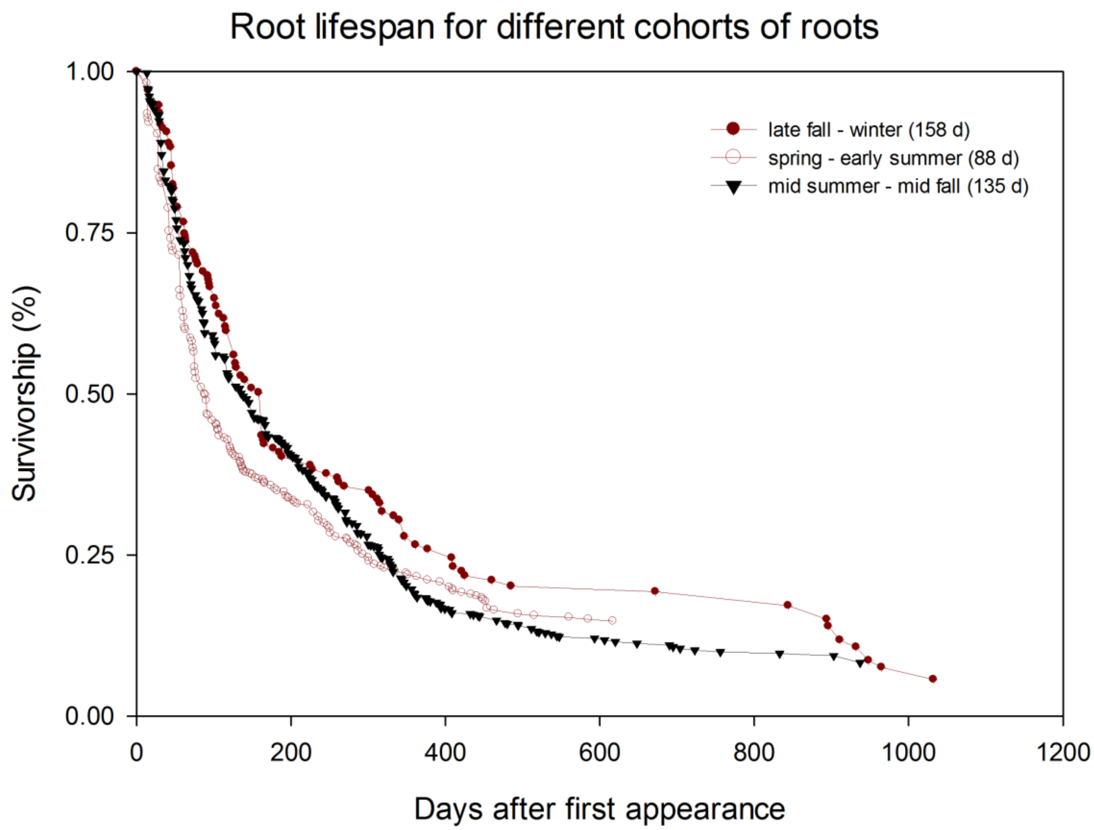

Figure 3-5 Root lifespan for different cohorts.

Chapter 4 – Fertigation with Drip and Alternative Micro Irrigation Systems in Highbush Blueberry: a Comparison of Point and Area Supply of Water and Nitrogen

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Abstract

The effects of nitrogen (N) fertigation using conventional drip and alternative micro irrigation systems were evaluated in six cultivars of northern highbush blueberry (*Vaccinium corymbosum* L.) during the first 3 years after planting (2009–2011). The cultivars, in order of ripening, were ‘Earliblue’ (July), ‘Duke’ (July), ‘Draper’ (July–August), ‘Bluecrop’ (August), ‘Elliott’ (August–September), and ‘Aurora’ (September). The drip system consisted of two laterals of drip tubing, with 2 $L \cdot h^{-1}$ in-line emitters spaced every 0.45 m (point source), placed on each side of the row at 0.2 m from the base of the plants. The alternative systems included a geotextile irrigation system and microsprinklers. The geotextile irrigation system was comprised of a single lateral of drip tape covered with a 10-cm-wide layer of geotextile fabric that dispersed water and nutrients along the entire length (broad band source); the lateral was located along the row directly near the base of plants. The microsprinkler system included 22.7 $L \cdot h^{-1}$ hanging fan-jet emitters located between every other plant at height of ≈1.2 m (full coverage). Liquid urea was injected weekly, from spring to mid-summer, at annual rates of 100 and 200 $kg \cdot ha^{-1}$ N by drip, 200 $kg \cdot ha^{-1}$ N by geotextile tape, and 280 $kg \cdot ha^{-1}$ N by microsprinklers. In year 1, plant size, in terms of percent canopy cover, was greatest in plants fertigated by geotextile tape (17%), on average, and smallest in those fertigated by drip at the lower N rate (9%) or microsprinklers (8%). By the following year, canopy cover was greatest in plants fertigated by drip at the high N rate (80%), similar between drip at the low N rate (72%) and geotextile tape (73%), and smallest in plants fertigated by microsprinklers (58%). However, there

were a few exceptions among the cultivars, including ‘Duke’ and ‘Aurora’, which had similar canopy cover in year 1 when plants were fertigated by geotextile tape and drip at the higher N rate, and ‘Draper’, which had similar canopy cover among each N treatment in year 2 but had less growth than other cultivars due to phytophthora root rot (especially with geotextile tape). In most cultivars, leaf N concentrations were within or just below the range considered ‘normal’ for blueberry (1.76-2.00% N) in plants fertigated by geotextile tape or drip at the higher N rate, but were often deficient (<1.50% N) with microsprinklers or drip at the lower N rate. By year 3, the first year of fruit production, yield averaged 3.1 $t \cdot ha^{-1}$ in ‘Earliblue’, 5.5–5.6 $t \cdot ha^{-1}$ in ‘Duke’ and ‘Draper’, 7.1 $t \cdot ha^{-1}$ in ‘Bluecrop’, 9.1 $t \cdot ha^{-1}$ in ‘Elliott’, and 6.4 $t \cdot ha^{-1}$ in ‘Aurora’; however, yield was similar among the drip (both N rates) and geotextile tape treatments and was only less with microsprinklers. Overall, establishment was similar between plants fertigated by drip and geotextile tape, and 100 $kg \cdot ha^{-1}$ N by drip was sufficient to maximize early fruit production. Fertigation with microsprinklers, on the other hand, produced less growth and yield than the other treatments and resulted in white deposits on the fruit.

Introduction

Fertigation, the application of fertilizers to plants through an irrigation system, is becoming a common practice in many crops worldwide (Bar-Yosef, 1999; Kafkafi and Tarchitsky, 2011). The practice often results in more growth and yield than equivalent rates of granular fertilizer, including in numerous perennial crops such as northern highbush blueberry (*Vaccinium corymbosum* L.) (Bryla and Machado, 2011; Ehret et al., 2014). With fertigation, nutrients are applied directly to the soil where roots are most concentrated, and both the concentration and balance of nutrients can be controlled more precisely (Bryla, 2011a). There is also less chance of over-fertilization and resultant salt injury, less soil compaction (no need for fertilizer spreaders), and reduced energy and labor costs (Burt et al., 1998). However, disadvantages of fertigation include higher fertilizer and equipment costs, increased water filtration requirements, greater risk for drip emitter plugging, and potential for soil water logging when the system is operated during cooler, wetter months.

While most blueberry fields in the United States have been irrigated historically using sprinklers, many new plantings are irrigated by drip, particularly in newer growing regions such as California, eastern Oregon, and Washington (Strik and Yarborough, 2005). Microsprinklers are also becoming a popular choice for irrigating blueberry plants grown on pine bark substrate in southeastern United States (J. Williamson, personal communication). In western Oregon, blueberry plants irrigated by drip required approximately half as much water as those irrigated by sprinklers or microsprinklers (Bryla et al., 2011) but had inferior fruit quality (softer fruit with lower soluble solids concentrations; Bryla et al., 2009) and greater potential for root rot (Bryla and Linderman, 2007). Drip also resulted in lower yields than microsprinklers in a 7-year study on blueberry in Chile (Holzapfel et al., 2004).

Soluble N fertilizers such as ammonium sulfate, urea ammonium nitrate, and liquid urea are easily injected and applied through drip and microsprinkler systems and are commonly used for fertigation in vine and perennial tree fruit crops (Schwankl et al., 1998). While fertigation targets relatively small soil volumes compared to traditional broadcast applications of granular fertilizers, fertigation through microsprinklers provides greater soil coverage and distributes nutrients more evenly than applications through most drip systems (Bar-Yosef, 1999; Elfving, 1982). Typically, only 20% to 30% of the total soil volume is wet by drip, and the wetting pattern is bulb-shaped, whereby soil water and availability of immobile nutrients such as ammonium (NH_4)-N decreases with increasing distance and depth from the drip emitter (Haynes, 1990).

Recently, several manufacturers began developing modified drip products such as geotextile irrigation systems to deliver a broad band source of water and nutrients to plants, rather than the point sources produced by standard drip systems. A typical geotextile irrigation system has an impermeable base sheet or layer usually made of polyethylene or polypropylene, a drip line along that base, and a layer of geotextile fabric over top of the drip line. The geotextile material facilitates mass flow and disperses irrigation water and nutrients over a larger area than drip, which potentially increases the efficiency of water and fertilizer applications (i.e., less deep percolation and nutrient leaching) (Charlesworth and Muirhead, 2003; Devasirvatham, 2008; Miller et al., 2000). A wider, uniform wetting pattern may be particularly beneficial in shallow-rooted crops such as blueberry (Bryla and Strik, 2007), because less water and nutrients will be lost below the root zone.

The objective of the present study was to determine the effects of N fertigation using a conventional drip configuration (two laterals per row) and two alternative micro irrigation systems, geotextile tape and microsprinklers, on shoot growth and early fruit production in northern highbush blueberry. Six cultivars were evaluated with each system, including two early- ('Earliblue' and 'Duke'), two mid- ('Draper' and 'Bluecrop'), and two late-season ('Elliott' and 'Aurora') types.

Materials and Methods

Study site. The study was conducted in a 0.27-ha field of northern highbush blueberry (*Vaccinium corymbosum* L.) planted on 9−10 Oct. 2008 at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, OR. Soil at the site is a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerolls). The soil contained 2.4% organic matter and was adjusted to pH 5.3 (1:2 soil:water; Sept. 2008) with two applications each of 670 $kg{\cdot}ha^{-1}$ of elemental sulfur, incorporated at 6 and 12 months prior to planting.

The plants were obtained from a commercial nursery (Fall Creek Farm & Nursery, Lowell, OR) as 18-month-old container stock and transplanted 0.76 m apart on raised beds (0.4 m high × 0.9 m wide) at a density of 4385 plants/ha. The beds were constructed using a bed shaper and centered 3.0 m apart. Approximately 8 cm of Douglas-fir (*Pseudotsuga menziesii* Franco) sawdust was incorporated 0.2 m deep in each row prior to shaping the beds (to increase soil organic matter), and 5 cm was applied on top of the beds immediately after planting (as mulch). Grass alleyways (1.5-

m wide) were planted between the beds the following spring and, once established, were mowed every 1–2 weeks during each growing season. Weeds were controlled, as needed, with glyphosate herbicide at the base of beds and by hand-weeding on the top of beds. Five cm of Douglas-fir sawdust was reapplied to the beds in Apr. 2011. Plants were sprayed with 5.6 $kg{\cdot}ha^{-1}$ of fosetyl aluminum fungicide (Aliette WDG; Bayer Crop Science, Research Triangle Park, NC) in May 2011 for phytophthora root rot control. No insecticides or other fungicides were applied to the plants. Honey bee (*Apis mellifera* L.) hives were located directly adjacent to the field year-round.

Experimental design. An irrigation system was installed prior to planting and was designed with a manifold to accommodate 24 different treatments. The treatments were arranged in a randomized complete block design, with five replications, and included a combination of six cultivars ('Earliblue', 'Duke', 'Draper', 'Bluecrop', 'Elliott', and 'Aurora') and four fertigation methods (fertigation at two N rates through drip systems and one N rate each through a geotextile irrigation system and microsprinklers). Each treatment plot contained one row of eight plants. Only the middle six plants in the plots were used for measurements in the drip and geotextile irrigation treatments, and only the four middle plants (where the wetting patterns overlapped) were used for measurements in the microsprinkler treatments. The planting contained a total of 1176 plants and included 12 rows of treatment plots, with two border plants on each end, and two border rows on each side of the planting.

The drip treatments were fertigated using a conventional drip irrigation system commonly used by many blueberry growers (personal observation and communication with irrigation designers). The system included a lateral of drip tubing (UniRam; Netafim USA, Fresno, CA) installed on each side of the row at a distance of ≈0.2 m from the base of the plants. The tubing had 2.0 $L \cdot h^{-1}$ pressure-compensating drip emitters integrated every 0.45 m, and was covered with the sawdust mulch following installation. The geotextile irrigation treatments were fertigated using a single lateral of poly drip tape enclosed between a 10-cm-wide layer of geotextile fabric on top and a layer of poly plastic of the same width on the bottom (4.2 $L \cdot min^{-1}$ per 100 m; BFF red; Irrigation Water Technologies America Inc., Longmont, CO). The tape was located along the row directly near the base of the plants (on the west side). Usually, geotextile tape is installed by burying it a few cm deep; however, since blueberry is a shallow-rooted crop and produces an abundance of roots at the interface between the soil and sawdust mulch (Bryla and Strik, 2007), the tape was placed fabric-side down on top of the soil surface and then was covered with sawdust mulch. The microsprinkler treatments were fertigated using 22.7 $L \cdot h^{-1}$ hanging fan-jet emitters (DC Series; Bowsmith, Exeter, CA) located between every other plant. To avoid interference with the plants, the emitters were suspended on a trellis wire ≈1.2 m above the plant canopy (year 1). The configuration produced a 2.7- to 3.0-m diameter, circular wetting pattern at operating pressures of 100−140 kPa [see Bryla et al. (2011) for further details].

Liquid urea (20–0–0), a common fertilizer used for fertigation in blueberry, was applied weekly to each treatment, beginning in the first week of May in 2009 and in the third week of April in 2010 and 2011, and finishing in the first week of August each year. The fertilizer was injected at the manifold using adjustable, 2.8 L differential pressure tanks (EZ-FLO Fertilizing Systems, Rocklin, CA). The drip treatments were fertigated with a total of 100 or 200 kg·ha^{-1} N per year, which, based on previous research on 'Bluecrop' blueberry, were considered low and optimum rates for fertigation during establishment (Bryla and Machado, 2011). The geotextile irrigation treatment was also fertigated at the higher rate of 200 kg·ha^{-1} N per year, while microsprinkler treatments were fertigated with 280 kg·ha^{-1} N per year. Additional N was applied by microsprinklers to compensate for the lower application efficiency of the system (≈40% of the water and fertilizer was applied between the rows and, therefore, was unavailable to the plants). Within a given fertigation treatment, N was applied at the same rate to each cultivar each week. For example, each cultivar fertigated by drip at the lower N rate received 7.14 kg·ha^{-1} N per week in 2009 (14 weekly applications) and 6.25 kg·ha^{-1} N per week in 2010 and 2011 (16 weekly applications).

Plants were irrigated from late May or early June to late September each year. Irrigation was controlled independently in each treatment using electric solenoid valves and an automatic timer, and was scheduled three to seven times per week, based on precipitation and estimates of crop evapotranspiration obtained from a local Pacific Northwest Cooperative Agricultural Weather Network AgriMet weather station (http://usbr.gov/pn/agrimet) (Bryla, 2011b). Water applications were monitored using water meters (Model SRII; Sensus, Raleigh, NC) installed at the inflow of each treatment and adjusted as needed to ensure that all treatments received enough irrigation to meet 100% of estimated crop water demands each week. Plants were fertigated during scheduled irrigation events. However, additional water (≈5 mm/wk) was needed for fertigation in early May 2009 and in April and May the following 2 years because rainfall was more than adequate for the crop during these periods.

Measurements. Canopy cover was estimated from digital images captured using an ADC multispectral camera (TetraCam, Chatsworth, CA) on 16−19 June and 13−14 Aug. in 2009 and on 23−25 May, 26−28 July, and 15−16 Sept. in 2010. The camera was suspended from a marked trellis wire located ≈2.5 m above the middle of each row, and the images were collected from every other plant in each plot for a total of 360 images per date. Percent live cover in the images was determined using software (Pixelwrench and Briv32) provided by the camera manufacturer. Care was taken to ensure that image area always exceeded canopy width in each image. Any cover by weeds or the grass alleyway was cleaned from the images using Adobe Photoshop v. 5.0 (Adobe Systems, San Jose, CA). Live cover was converted to total percent canopy cover based on the proportion of the field covered by each image.

Plants were pruned in February each year with the goal of balancing vegetative and fruit production and to allow no fruit production until the third growing season in 2011. Ripe fruit were hand-picked , beginning with ‘Earliblue’ and ‘Duke’ on 11, 18, and 25 July, ‘Draper’ on 25 July and 8 Aug., ‘Bluecrop’ on 1 and 15 Aug., ‘Elliott’ on 29 Aug. and 9 and 22 Sept., and ‘Aurora’ on 2, 13, and 28 Sept. 2011. The fruit were weighed on each harvest date, to determine the marketable yield in each treatment, and a random subsample of 100 berries was weighed, to determine the average berry weight in each plot. Any non-marketable fruit (green, red, or damaged berries), including any small, green berries remaining after the final harvest in each cultivar, were discarded.

Leaf samples were collected during the first week of August each year and analyzed for N. Six recently-mature leaves were removed and pooled together from each of the center four (microsprinklers) or six (drip and geotextile tape) plants in each plot, oven-dried at 70^{o} C, ground, and analyzed for total N using a combustion analyzer (model CNS-2000; LECO Corp., St. Joseph, MI).

A number of 'Draper' plants had stunted growth and poor leaf color (i.e., yellowing and premature reddening) beginning in the second year after planting (2010). Symptoms were consistent with phytophthora root rot (Caruso and Ramsdell, 1995). Therefore, roots were sampled from three healthy and five unhealthy plants (one from each replicate treatment plot) and assayed for *Phytophthora* by removing a subsample of soil (5 $cm^2 \times$ 15 cm deep) located within 15 cm from the base of the plants. Two methods were used to isolate and identify the pathogen using both roots and soil from the samples. Roots were washed free of the soil in running tap water and then surface disinfected for 2 min in 70% ethanol solution, before plating 10, 1-cm-long root segments per plant on PARP, a semi-selective medium for Pythiaceous species (Kannwischer and Mitchell, 1978). Soil was baited with leaf disks of *Rhododendron* 'Unique', according to previously established methods (Weiland, 2011). Fifteen mL of soil from each plant was placed into a 150-mL waxed paper cup. A second paper cup with the bottom cut out and replaced with a double layer of cheesecloth was positioned over the soil sample, and then 50 mL of distilled water was added. Twelve 5-mm-diameter leaf disks were then floated on the water surface in each cup for 2 d before plating them on PARP. The plates were incubated in the dark at 20 °C and then examined daily for colonies of *Phytophthora* species for at least 7 d. Isolates were identified as *P. cinnamomi* by morphological characteristics, according to the taxonomic keys of Stamps et al. (1990), and confirmed by sequencing (Macrogen, Korea) the internal transcriber spacer (ITS) region of each isolate and comparing the resultant sequence to that published by Cooke and Duncan (1997). Plants displaying symptoms of the disease were counted from the six middle plants in each plot on 11 Nov. 2010. 'Draper' was the only cultivar with symptoms.

Statistical analysis. All data were analyzed by analysis of variance (ANOVA) using the PROC MIXED procedure in SAS (Version 9.3; SAS Institute Inc., Cary, NC). Means were separated at the 0.05 level using Tukey-Kramer HSD test. To account for the heterogeneity structure in each dataset, cultivars with highly variable values such as 'Draper' were assigned independent variance parameters (Little et al., 2006). The incidence of root rot symptoms in 'Draper' plants was evaluated in 2010 by the χ^2 test of independence using the PROC FREQ procedure in SAS to determine if symptoms were independent of fertigation treatment. 'Draper' was subsequently subsampled between healthy (no root rot symptoms) and unhealthy plants the following year, and only the healthy plants were included in the analysis of leaf N and fruit production in year 3 (2011).

Results

Plant growth. Canopy cover, which is a good representation of plant development in a new planting, increased from ≤ 8% for each cultivar in June 2009 (year 1) to as much as 58% to 89% by Sept. 2010 (Figure 4-1). On average, canopy cover was greatest when plants were irrigated and fertigated by geotextile tape during the first year after planting ($\overline{X}_{\text{Aug.}}$ = 17%) and by drip at the higher N rate the following year ($\overline{X}_{\text{Sept.}}$ = 80%), and was lowest with microsprinklers or drip at the lower N rate during the first year ($\overline{X}_{\text{Aug.}}$ = 8% and 9%, respectively) and by microsprinklers the second year ($\overline{X}_{\text{Sept.}}$ = 58%). Significant interactions between fertigation method and cultivar on May 2010 (P = 0.0108) and Sept. 2010 (P = 0.0186) indicate that the plant response to the different methods varied somewhat among the cultivars. For example, while four cultivars had more canopy cover with drip or geotextile tape than with microsprinklers in Sept. 2010, percent cover in 'Duke' only differed between plants fertigated by drip at the higher N rate and those fertigated by microsprinklers, and 'Draper' was similar among each method (Figure 4-1).

Most plants in the study were healthy and vigorous. However, as mentioned, a number of the 'Draper' plants had poor growth the second year, and all five of the sampled symptomatic plants were infected by *P. cinnamomi*, the causal pathogen associated with root rot in blueberry (Caruso and Ramsdell, 1995). None of the healthy plants sampled were found to be infected by *P. cinnamomi*. A χ^2 test revealed that root rot symptoms in the cultivar were not independent of the fertigation method (P = 0.0473). The use of geotextile tape resulted in approximately twice as many plants exhibiting symptoms of root rot than either drip treatment or microsprinklers (Table 4-1).

Leaf N concentrations. The response of leaf N to the fertilizer treatments varied among the cultivars and resulted in a significant interaction each year ($P \leq 0.05$; Figure 4-2). For example, during the first year after planting (2009), leaf N concentration was similar among each of the fertilizer treatments in 'Bluecrop', as well as between the two N rates with drip in 'Elliott', and only differed between geotextile tape and microsprinklers in the late-season cultivars, 'Elliott' and 'Aurora'. The following year, leaf N was similar between drip (regardless of N rate) and geotextile tape in each cultivar, and only differed between the two drip treatments in 'Earliblue' and 'Draper', and between geotextile tape and microsprinklers in 'Bluecrop'. By the third year, leaf N continued to be similar among the fertilizer treatments in 'Duke' and 'Elliott', as well as in 'Aurora' at that point, and only differed between the two drip treatments in 'Earliblue', 'Draper', and 'Bluecrop', and between geotextile tape and microsprinklers in 'Earliblue'.

In most of the cultivars, leaf N was within or slightly below the range considered 'normal' for blueberry (1.76% to 2.00% N; Hart et al., 2006) when plants were fertigated by drip at the higher N rate or by geotextile tape, but often deficient (<1.50% N) when plants were fertigated by drip at the lower N rate or by microsprinklers (Figure 4-2). Leaf N was also lower and often more deficient in 2010 ($\overline{X}_{\mathrm{All}}$ = 1.48%) than in 2009 or 2011 ($\overline{X}_{\mathrm{All}}$ = 1.65% and 1.62% N, respectively). This was particularly the case in 'Draper', which, as mentioned, was hampered by root rot in 2010 (Table 4-1). Leaves sampled from only healthy ‘Draper’ plants the following year (2011) had much higher N concentrations (1.39% in 2010 vs. 1.75% in 2011).

Early fruit production. Marketable yield differed among the fertilizer treatments in 2011 during the first year of fruit production and, on average, was 31% greater when plants were fertigated by geotextile tape or drip at the higher N rate than by microsprinklers (Table 4-2). However, yield was similar between N rates when plants were fertigated by drip, and also similar between plants fertigated by drip at the lower N rate and those fertigated by microsprinklers. ‘Elliott’ produced the highest yield among the cultivars, while ‘Earliblue’ produced the lowest yield (Table 4-2).

Berry weight also differed among the cultivars, but unlike yield, it was similar among the fertigation treatments (Table 4-2). In most cases, appearance of the fruit was excellent and suitable for fresh market. However, many berries from plants fertigated by microsprinklers were covered with white salt deposits from the fertilizer, and, therefore, would only have been suitable for the processed market.

Discussion

During the first year after planting, a single lateral of geotextile tape resulted in more plant growth (both visually and based on canopy cover) than two lines of drip in four out of six cultivars, including ‘Earliblue’, ‘Draper’, ‘Bluecrop’, and ‘Elliott’, while fertigation with microsprinklers produced the least growth in each cultivar. More growth with geotextile tape may have been a result of the even distribution of water and fertilizer along the row but was more likely due to the position of the irrigation lines. With the geotextile tape, N was applied near the base of the plants, and since

NH_4-N, which is the primary form of N acquired by blueberry (Claussen and Lenz, 1999), is relatively immobile in soil, application with drip may have placed the fertilizer too far from the roots of the young plants. However, increasing the N rate with drip from 100 to 200 $kg \cdot ha^{-1}$ N improved leaf N and plant growth considerably the first year. Fertigation with microsprinklers appeared to be even less efficient than drip (see below).

By the second year after planting, plant size was similar between the high N drip and the geotextile tape treatments in each cultivar, as well as between the drip treatments fertigated with low and high N rates in all but ‘Aurora’. Yield was also similar among these treatments the following year. While it was not measured in the study, the root systems of the plants were likely much larger by the beginning of the second season than in the previous year, and roots were probably concentrated near the drip emitters (Bryla, 2011a). If so, more of the N applied through the drip system would have been available for root uptake and, therefore, would explain why less N (i.e., 100 $kg \cdot ha^{-1}$) was needed in plants fertigated by drip in the second year. Only 67–93 $kg \cdot ha^{-1}$ N was required by fertigation to maximize yield in a mature field of ‘Bluecrop’ blueberry (O. Vargas and D. Bryla, unpublished data). Microsprinklers, on the hand, continued to result in the smallest plants in most cultivars and produced lower yields than high N drip and geotextile tape. This indicates that the efficiency of N fertigation through the microsprinklers was lower than the 40% loss estimated based on bed coverage. The fertilizer N was not only spread over a much larger area with microsprinklers than with the other systems, it was also applied on top of the sawdust mulch and, therefore, probably partially immobilized by microbial decomposition (Jackson et al., 2009). Potential strategies for increasing the efficiency of the microsprinklers may include the use of more emitters per row, emitters with a lower flow rate or a narrower wetting pattern, a lower emitter placement height, and the use of “top hats” (Bowsmith, Exeter, CA), which affix to the top of the emitters and restrict the spray diameter.

The N rates used in the present study were much higher than those typically recommended when using granular fertilizers in highbush blueberry. For example, in Oregon, Hart et al. (2006) recommend applying 17–26 g/plant of granular N to a planting without sawdust mulch during the first 4 years after planting, which, at the plant spacing used in this study, is equivalent to ≈60–90 $kg \cdot ha^{-1}$ N per year. Higher N rates are recommended initially for fertigation due to low application efficiency in young plantings (Bryla and Machado, 2011). Even when a drip line is located near the base of the plants, over half of the emitters in a standard 0.30–0.45 m spacing configuration will end up between the plants and outside of the root zone during the first after planting. Therefore, much of the NH_4-N will be unavailable to the plants. Most of this unavailable N will then convert to NO_3-N and eventually leach from the soil with rain and irrigation (Bryla et al., 2010).

While yield differed among the six cultivars in the study, the yield response of each cultivar to the fertigation methods was similar. On average, yields ranged from 3.1 $t \cdot ha^{-1}$ in the early-season cultivar, ‘Earliblue’, to 9.1 $t \cdot ha^{-1}$ in the late-season cultivar, ‘Elliott’. These yields are comparable to what is commonly observed in commercial fields at this stage of establishment (B.C. Strik, personal communication). Nitrogen requirements per kg of fruit produced thus varied among the cultivars, which probably affected the amount of N required to maximize growth and fruit production. On average, leaf N concentrations were highest in year 1 and 2 in the early-season cultivars, 'Earliblue' and 'Duke', and lowest in the late-season cultivars, 'Elliott' and 'Aurora'. However, during first fruiting season in year 3, leaf N concentrations were highest in the mid-season cultivars, 'Draper' and 'Bluecrop', and similar between the early- and late-season cultivars.

In terms of yield, the most efficient system used in the study was drip at the lower N rate (100 $kg \cdot ha^{-1}$ N). In order of ripening, the N required to produce 1 kg of fruit was 32, 18, 18, 14, 11, and 16 g/plant for 'Earliblue', 'Duke', 'Draper', 'Bluecrop', 'Elliott', and 'Aurora', respectively. Therefore, the total amount of N applied by drip and geotextile tape at the higher N rate (200 $kg \cdot ha^{-1}$ N) was excessive at the site, particularly in the lower yielding cultivars. However, despite the greater efficiency obtained with the lower N rate, leaf N was below normal each year in this treatment, especially in the higher yielding cultivars, 'Elliott' and 'Aurora'. This may indicate that N standards should be lower when the plants are fertigated than previously reported for blueberry (Hart et al., 2006).

While most plants were healthy in the study, 'Draper' developed root rot symptoms in the second year and were found to be infected by *P. cinnamomi*, a highly virulent root rot pathogen of highbush blueberry that is present in most growing regions worldwide (Strik and Yarborough, 2005). In a survey of 55 commercial blueberry fields in Oregon, *P. cinnamomi* was detected in 24% of the fields (Bryla et al., 2008). Susceptibility to the pathogen varies among cultivars and increases under wet soil conditions. Yeo (2014) recently exposed 18 cultivars and three advanced selections of highbush blueberry to *P. cinnamomi* under greenhouse conditions and determined that 'Draper' was among the most susceptible cultivars evaluated. In this study, disease incidence was nearly double when plants were irrigated and fertigated with the geotextile tape. The tape likely resulted in wetter soil conditions near the base of the plant and, consequently, was more conducive to infection. Bryla and Linderman (2007) found similar results when drip lines were placed near the base of the plants.

Conclusions

Although leaf N was lower than the recommended standard, blueberry establishment and yield was most efficient when the plants were fertigated by drip at the lower N rate (100 $kg \cdot ha^{-1}$ N). While geotextile tape was also effective, particularly during the first year after planting, it was more costly and produced more-or-less the same amount of growth and yield as drip the following 2 years. Geotextile tape also increased the incidence of root rot in 'Draper'. Fertigation with microsprinklers, on the other hand, reduced yield and berry quality (white deposits on the berries) in each cultivar and resulted in much lower N efficiency than the other treatments. Installing the microsprinklers at a lower height may help circumvent these problems. While drip was clearly the best system for fertigation of blueberry in the present study, the alternative systems could have advantages in sandier soils where lateral movement of water and nutrients is more limited (e.g., Patten et al., 1988). Therefore, further testing of these systems in other soil types is warranted.

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Tables and Figures

Table 4-1 Unhealthy plants displaying symptoms of phytophthora root rot in 'Draper' blueberry. Plants were fertigated through a drip irrigation system at a rate of 100 or 200 kg·ha^{-1} N per year, a geotextile irrigation system at a rate of 200 kg·ha^{-1} N per year, or a microsprinkler system at a rate of 280 kg·ha^{-1} N per year.

Fertigation method	Unhealthy plants[z] (%)
Drip (100 kg·ha^{-1} N)	20
Drip (200 kg·ha^{-1} N)	23
Geotextile tape (200 kg·ha^{-1} N)	50
Microsprinkler (280 kg·ha^{-1} N)	27

Healthy vs. unhealthy plants:

$\chi^2 = 7.93$ df = 3 $P = 0.0473$

[z]Six plants from each treatment plot were evaluated for root rot symptoms (n = 30). Symptoms included stunted growth, pale yellow to reddish leaves, marginal leaf necrosis, and premature defoliation.

Table 4-2 Yield and individual berry weight of early- ('Earliblue' and 'Duke'), mid- ('Draper' and 'Bluecrop'), and late-season ('Elliott' and 'Aurora') cultivars of highbush blueberry during the first year of fruit production in 2011 (year 3). Each cultivar was fertigated through a drip irrigation system at a rate of 100 or 200 kg·ha^{-1} N per year, a geotextile irrigation system at a rate of 200 kg·ha^{-1} N per year, or a microsprinkler system at a rate of 280 kg·ha^{-1} N per year.

Treatment	Yield (kg/plant)	Berry wt[z] (g)
Fertigation method		
Drip (100 kg·ha^{-1} N)	1.40 ab[y]	2.04
Drip (200 kg·ha^{-1} N)	1.54 a	1.98
Geotextile (200 kg·ha^{-1} N)	1.57 a	1.98
Microsprinkler (280 kg·ha^{-1} N)	1.19 b	2.02
Significance	0.0003	NS
Cultivar		
Earliblue	0.72 d	1.94 b
Duke	1.30 c	2.07 ab
Draper	1.27 c	1.93 b
Bluecrop	1.65 b	2.13 a
Elliott	2.12 a	1.85 c
Aurora	1.48 bc	2.12 a
Significance	<0.0001	<0.0001
Interaction		
Fertigation method × cultivar	NS	NS

[z]Berry weight was averaged over each harvest, and the mean was weighted based on yield.

[y]Means (n = 5) followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey's HSD test.

[NS]Nonsignificant.

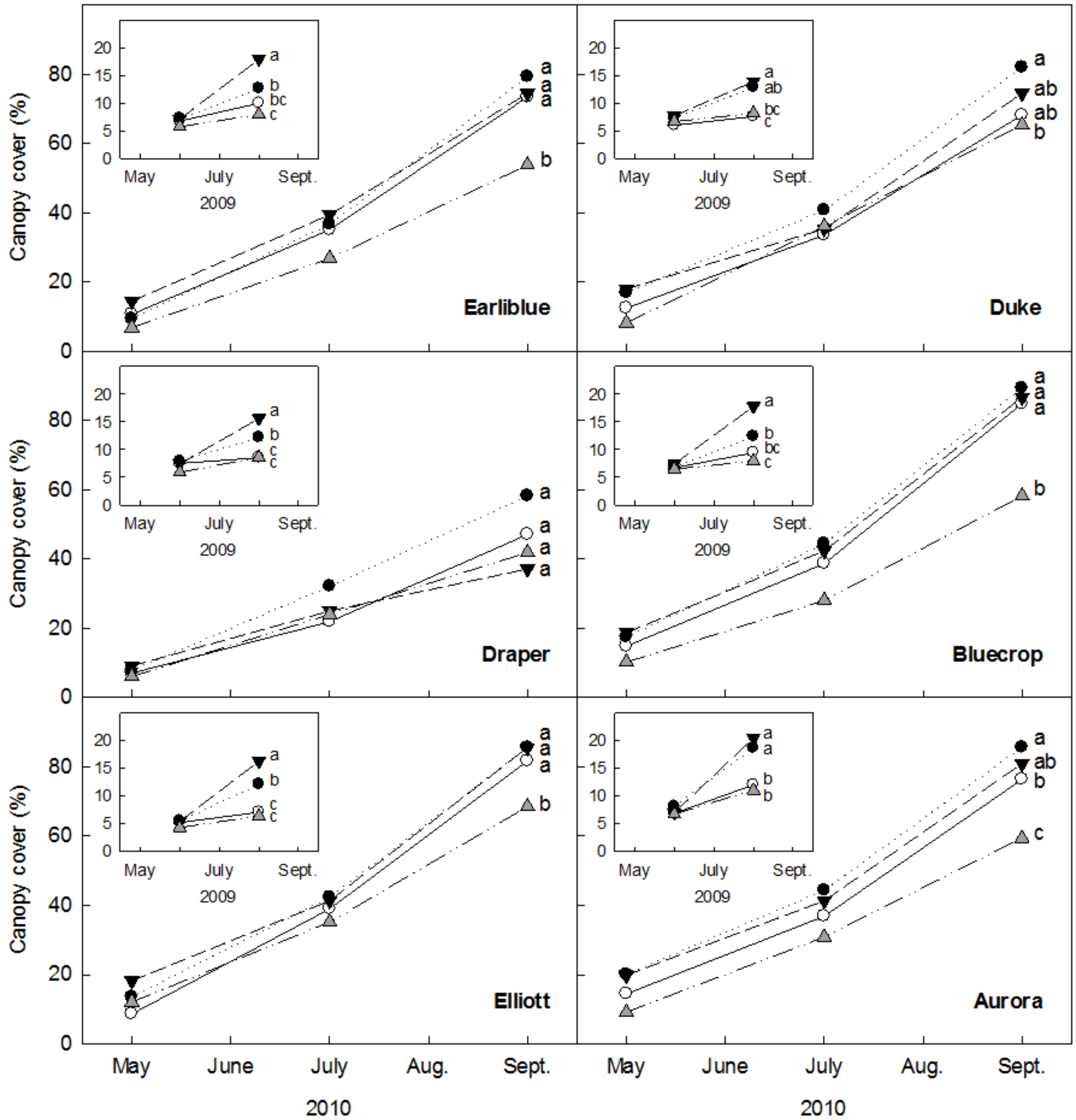

Figure 4-1 Canopy cover of early- ('Earliblue' and 'Duke'), mid- ('Draper' and 'Bluecrop'), and late-season ('Elliott' and 'Aurora') cultivars of highbush blueberry fertigated through a drip irrigation system at a rate of 100 (○) or 200 (●) kg·ha^{-1} *N, a geotextile irrigation system at a rate of 200 kg·ha*$^{-1}$ *N (▼), or a microsprinkler system at a rate of 280 kg·ha*$^{-1}$ *N (△) during the first (2009; insets) and second year (2010) after planting. Each symbol represents the mean of five replicates, and means with different letters in Aug. 2009 and Sept. 2010 were significantly different at* $P \leq 0.05$*, according to Tukey's HSD test.*

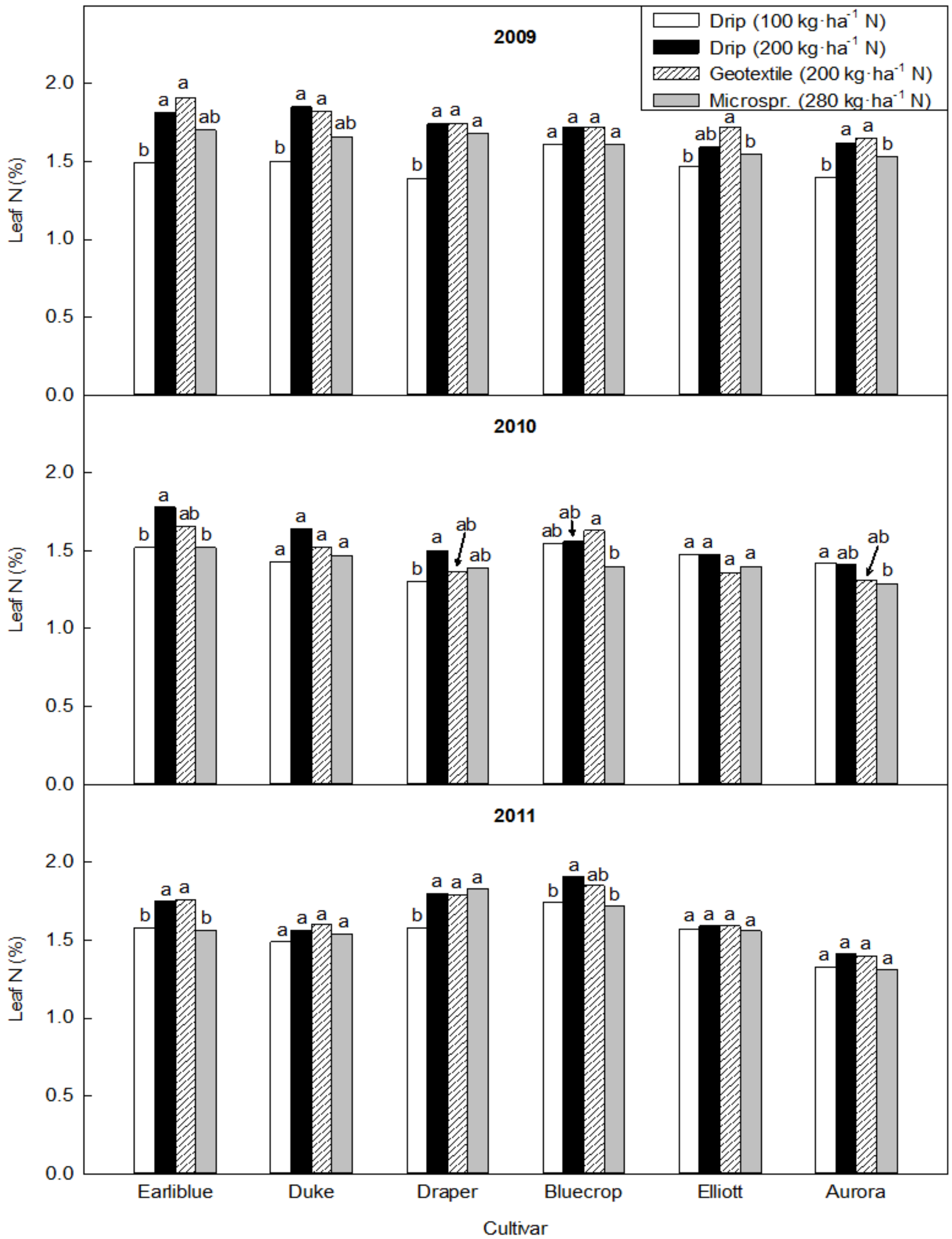

Figure 4-2 Leaf N concentrations of early- ('Earliblue' and 'Duke'), mid- ('Draper' and 'Bluecrop'), and late-season ('Elliott' and 'Aurora') cultivars of highbush blueberry during the first 3 years after planting (2009–2011). Each cultivar was fertigated through a drip irrigation system at a rate of 100 or 200 kg·ha^{-1} N, a geotextile irrigation system at a rate of 200 kg·ha^{-1} N, or a microsprinkler system at a rate of 280 kg·ha^{-1} N. Each bar

represents the mean of five replicates, and different letters above the bars indicate that means within a cultivar are significantly different at $P \leq 0.05$, according to Tukey's HSD test.

Chapter 5 - Fertigation and Alternative Fertilizer Practices for Rapid Establishment of Highbush Blueberry

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Abstract

Fertigation or injection of fertilizers through the irrigation system is becoming common practice in many horticultural crops. The objective of this study was to identify fertigation and alternative fertilizer practices to increase growth and early production in northern highbush blueberry (*Vaccinium corymbosum* L.). Plants were fertigated for 2 years in western Oregon using four different drip configurations, including one line of drip tubing or geotextile tape placed near the base of the plants or two laterals of drip tubing placed at 5 cm (narrow) or 20 cm (wide) from the plant base on each side of the row. In each case, plants were fertigated from late April to late July with equal applications of liquid urea at a total rate of 100 $kg{\cdot}ha^{-1}$ of nitrogen (N) per year. Six alternative fertilizers and supplements were also evaluated, including fertigation through narrow drip lines using urea sulfuric acid, urea + humic acids, and urea + phosphorus (P) + zinc (Zn), each at a rate of 100 $kg{\cdot}ha^{-1}$ N per year, and fertigation through wide drip lines using either two applications of granular urea (10 $kg{\cdot}ha^{-1}$ N each in April and May) followed by fertigation for 2 months with 80 $kg{\cdot}ha^{-1}$ N from liquid urea or a single application of controlled-release polymer coated urea (60 $kg{\cdot}ha^{-1}$ N in late April) followed, or not, by fertigation for 1.5 months with 40 $kg{\cdot}ha^{-1}$ N from liquid urea. We also investigated whether pre-plant granular N or late-season applications of N by fertigation had any effect on growth or fruit production. Total plant dry weight was 28% to 58% greater each year when plants were fertigated with one or two drip lines or tape located near the base of the plants than with two wide drip lines. Wide drip lines also resulted in lower leaf N concentrations and

increased electrical conductivity (salinity) of the soil solution near the base of the plants to levels as high as 3 $dS \cdot m^{-1}$. Urea sulfuric acid was effective at reducing soil pH but resulted in the same plant dry weight as liquid urea, while humic acids increased root dry weight by an average of 60% relative to the other treatments. Granular and polymer coated urea did not improve plant growth or yield with wide drip lines and was less effective than any of the treatments with narrow drip lines. Pre-plant and late-season applications of N fertilizer also had no effect on growth, yield, fruit bud set, or leaf nutrient concentrations. Overall, the results indicate that drip lines should be located near the base of the plants during establishment of highbush blueberry, and supplementing fertigation with humic acids may help improve root production.

Introduction

Fertigation is becoming the preferred method of nutrient application in many horticultural crops, including highbush blueberry. With fertigation, nutrients are applied directly to a small, wetted soil volume, where many of the roots are concentrated, and both the concentration and balance of nutrients can be controlled more precisely (Bryla, 2011a). However, depending on soil type, emitter discharge rate, and drip line placement (distance from plants), the application of nutrients from a point source may produce variations in soil nutrient distribution within the wetted volume (Alva and Syvertsen, 1991; Bar-Yousef, 1999; Goldberg et al., 1971). In contrast, granular applications of nitrogen (N) fertilizer have been shown to generate high concentrations of N and other nutrients in the soil solution, resulting in high salinity, measured by electrical conductivity (EC), as well as nutrient imbalances and toxicities (Bryla and Machado, 2011; Haynes, 1990; Robinson, 1994; Vargas and Bryla, 2015). High salinity in the rhizosphere of salt-sensitive crops, such as blueberry, reduces shoot and root growth, yield, and fruit quality (Bryla and Machado, 2011; Grattan and Grieve, 1999; Goldberg et al., 1971).

Generally, plants absorb both the ammonium (NH_4) and nitrate (NO_3) forms of N, and media pH may be affected by the form of N applied. Cain (1952), and Herath and Eaton (1968) observed better growth in highbush blueberry with NH_4-N than with NO_3-N. Blueberry plants acquire primarily the NH_4-N form of N (Claussen and Lenz, 1999). Although blueberry has low nutrient requirements compared to many other fruit crops, it typically needs regular applications of N fertilizer to maximize growth and fruit production (Bañados et al., 2012; Hanson and Hancock, 1996; Vargas and Bryla, 2015).

In addition to the common N fertilizers such as urea and ammonium sulfate, many growers are using newer products such as controlled-release polymer-coated urea (PCU), urea sulfuric-acid, and humic acids for blueberry. The release of N and other nutrients from PCU is controlled mostly by temperature and moisture, which also favor crop development. Ideally, the release period and pattern should match crop N uptake (Carson and Ozores-Hampton, 2013; Shaviv, 2001). Urea sulfuric acid is well suited to blueberry because ammonium is released quickly and sulfuric acid helps acidify the soil (Bryla et al., 2010). The benefits of humic acids on plant growth have been reported in a number studies (Rauthan and Schnitzer, 1981), usually in low organic matter soils, sand culture, or hydroponic production system (Chen et al., 2004). Some have also reported benefits of humic acids under agricultural conditions (Rose et al., 2014), but no study to date has been conducted in blueberry.

Incorporation of sawdust or compost prior to planting has been a common industry practice in highbush blueberry. Sawdust has a high carbon to N ratio (>600). Soil microbes require N for sawdust decomposition and are more efficient at using available soil N than plants. Therefore, recommendations are to apply N fertilizer with any sawdust incorporated prior to planting, leaving sufficient N for the newly transplanted blueberry plants (Hart et al., 2006). In addition, recommendation are to discontinue N fertilizer applications by mid-summer, as later applications may reduce fruit bud set and produce late-season growth susceptible to winter injury.

Previously, we found that applying N by fertigation through a drip irrigation system resulted in greater yield in northern highbush blueberry than conventional granular applications of N fertilizer, but it was less efficient in terms of the amount of N required for growth during establishment (Bryla and Machado, 2011; Vargas and Bryla, 2015). More N was needed by fertigation, in this case, because unlike granular fertilizer, which could be applied by hand around the base of the plants, at least half of the urea or NH_4-N injected through the drip system was applied between the plants and beyond the root zone during first year or two after planting. In a second study on six cultivars of blueberry, we found that using two laterals of drip, which is now the common practice in highbush blueberry, was even worse than the single line used in the previous study because emitters and; therefore, the applied N were located even further from the roots of the young plants (Vargas et al., 2015). The work indicated that new methods were needed to apply the N fertilizer closer to the roots in young plants.

The objective of the present study was to identify fertigation and alternative fertilizer practices that increase the availability of NH_4-N and other nutrients in the rhizosphere to increase growth and early fruit production during establishment of highbush blueberry. We investigated the use of different drip system configurations, humic acid supplements, controlled-release fertilizer (PCU), and small applications of granular fertilizer applied prior to fertigation. We also determined if there was any benefit of using pre-plant N fertilizer and examined whether there was an impact of late-season fertigation with N.

Materials and methods

Study site. A field of ‘Draper’ blueberry was planted on 13 Oct. 2010 at the Oregon State University Lewis-Brown Horticultural Research Farm in Corvallis, OR. The soil at the site was a Malabon silty clay loam (fine, mixed, superactive, mesic Pachic Ultic Argixerolls) that had a pH 6.1 and 2.4% organic matter. To reduce soil pH, elemental sulfur was incorporated into the top 20 cm of soil at 6 and 10 months prior to planting in equal applications of 650 $kg{\cdot}ha^{-1}$ each. The plants were obtained from a commercial nursery (Fall Creek Farm & Nursery, Lowell, OR) and transplanted 0.76 m apart on raised beds (0.4 m high × 0.9 m wide). The beds were constructed with a bed shaper and centered 3.0 m apart. Prior to shaping the beds, ≈8 cm of Douglas-fir (*Pseudotsuga menziesii* Franco) sawdust was incorporated 0.2 m deep in each row to increase the organic matter content in the root zone. Granular ammonium sulfate was also mixed into the soil with the sawdust prior to planting at a rate 105 $kg \cdot ha^{-1}$ N, except in one case where no pre-plant N was added (see below). A 5-cm layer of Douglas-fir sawdust mulch was applied on top of the beds immediately after planting.

We previously found that ‘Draper’ blueberry was susceptible to *Phytophthora* root rot at establishment (Vargas et al., 2015). Therefore, to prevent root rot, the planting beds were drenched with 0.39 $mL \cdot m^{-1}$ of mefenoxam fungicide (Ridomil Gold SL; Syngenta Crop Protection, Greensboro, NC) on 10 Nov. 2010, and the plants were sprayed with 5.6 $kg \cdot ha^{-1}$ of fosetyl aluminum fungicide (Aliette WDG; Bayer Crop Science, Research Triangle Park, NC) on 17 Mar. 2011. No insecticides or other fungicides were applied to the plants during the study. Grass alleyways (1.5-m wide) were planted between the beds in Apr. 2011 and mowed every 1–2 weeks during each growing season. Weeds were controlled using glyphosate herbicide at the base of beds and by hand-weeding on the top of beds.

Experimental design. Twelve treatments were arranged in a randomized complete block design with one row per block. The treatments included four drip configurations, six alternative fertilizers, one treatment to examine the impact of using no pre-plant N fertilizer, and one treatment to determine whether late-season applications of N fertilizer affected fruit bud set or increased winter injury. Each treatment plot consisted of one row of six plants and was replicated five times. The four center plants in each plot were used for measurements, and the remaining two plants were treated as border plants. Two additional border plants were transplanted at the end of each row, and a border row was transplanted on each side of the planting.

The four drip configurations included one line of drip tubing (Netafim USA, Fresno, CA) or geotextile tape (Irrigation Water Technologies America Inc., Longmont, CO) installed along the row near the base of the plants, or two lines of the drip tubing installed at either 5 cm (narrow) or 20 cm (wide) from each side of the plants. Each treatment was fertigated once a week from late April to late July with liquid urea (20N–0P–0K). The same amount of N was applied to each treatment each week at a total rate of 100 $kg \cdot ha^{-1}$ N per year. The drip tubing had in-line, 2.0 $L \cdot h^{-1}$ pressure-compensating drip emitters located at every 0.45 m. The geotextile tape had a flow rate of 6.6 $L \cdot min^{-1}$ per 100 m and consisted of a single lateral of poly drip tape enclosed between a 10-cm-wide layer of geotextile fabric on one side and poly plastic on the other side. The tape was placed fabric-side down on top of the soil surface and was covered with sawdust mulch. The drip lines were also covered with sawdust mulch.

The alternative fertilizers included three treatments with two narrow drip lines and three treatments with two wide drip lines. The treatments with the narrow lines were fertigated weekly from late April to late July using either urea sulfuric acid (15N−0P−0K−15S), liquid urea supplemented with humic acids (Actagro Plant Nutrients, Fresno, CA), or liquid urea supplemented with P and Zn fertilizers. Each fertilizer was applied once a week from late April to late July with equal amounts of N at a total rate of 100 $kg \cdot ha^{-1}$ N per year. The humic acid treatment was developed by the manufacturer for commercial blueberry fields in western Oregon and included three liquid products containing N, P, K, and Zn. The liquid products were received individually and mixed together each week. They included one supplement containing N and P (7N–9.2P–0K) and 5% humic acids (Structure), a second supplement with 6.5% Zn and 2.5% humic acids (6.5% Zn), and a third supplement with K (0N–0P–1.7K) and 5% humic acids (Plant Plus). Together, these products supplied a total of 8.4 $kg \cdot ha^{-1}$ N, 10.6 $kg \cdot ha^{-1}$ P, 0.12 $kg \cdot ha^{-1}$ K, 0.16 $kg \cdot ha^{-1}$ S, 0.6 $kg \cdot ha^{-1}$ Zn, and 6.3 $kg \cdot ha^{-1}$ of humic acids. A control for this treatment was designed in order to supply the same amount of nutrients, but without humic acids. The control included liquid ammonium polyphosphate (10N–14.9P–0K) and zinc chelates (9% Zn). However, no K or S was included in the control treatment since the amounts applied in the humic acid program were relatively minor. Liquid urea was added to both treatments to reach 100 $kg \cdot ha^{-1}$ N. The treatments with the wide drip lines were fertilized with either two applications of granular urea (46N−0P−0K) applied at a rate of 10 $kg \cdot ha^{-1}$ N in each of late April and early May followed by weekly fertigation from mid-June to late July with 80 $kg \cdot ha^{-1}$ N from liquid urea, or one application of controlled-release polymer coated urea (44N–0P–0K; Agrium U.S. Inc., Denver, CO) applied at a rate of 60 $kg \cdot ha^{-1}$ N in late April only or followed by weekly fertigation from mid-June to late July with 40 $kg \cdot ha^{-1}$ N from liquid urea. The granular and poly coated urea were spread uniformly around the plants in a radius of ≈0.15 m.

The two remaining treatments were also fertigated once a week through two narrow drip lines using liquid urea but, in this case, either 1) had no pre-plant N fertilizer or 2) were fertigated from late April to mid-September rather than to late July. A total of 100 kg·ha^{-1} N was applied to both treatments each year.

Each liquid fertilizer was injected at the manifold using adjustable, 2.8-L differential pressure tanks (EZ-FLO Fertilizing Systems, Rockling, CA). The fertilizers were applied at the same N rate each week within a given fertigation treatment. For example, in treatments fertigated from late April to late July with a total 100 kg·ha^{-1} N, the fertilizer was divided into 14 equal applications of 7.14 kg·ha^{-1} N each.

The plants were irrigated from 12 June to 30 Sept. in 2011 and from 14 May to 30 Sept. in 2012. Irrigation was controlled independently in each treatment using electronic solenoid valves and an automatic timer, and was scheduled three to seven times per week based on precipitation and estimates of crop evapotranspiration obtained from a local agricultural weather station (http://usbr.gov/pn/agrimet). Water applications were monitored at least weekly, using water meters (Model DRII; Sensus, Raleigh, NC) installed at the inflow of each treatment, and were adjusted as needed to ensure the treatments received enough rain or irrigation to replace 100% of estimated water demands each week (Bryla, 2011b). An additional ≈5 mm/week of water was applied to each treatment for fertigation during the weeks in which rainfall was more than adequate for the crop.

The plants were pruned in February each year. Fruit production is commonly limited during the first year or two after planting in highbush blueberry to encourage more vegetative growth during establishment (Strik and Buller, 2005). Therefore, all of the flower buds were pruned from the plants the first year, and 30–50 flower buds were left on the plants during the following year, a standard commercial practice in many commercial fields (Julian et al., 2011; B.C. Strik, personal observations). Fruit bud set was measured in December of each year by counting the number of vegetative buds and flower buds on two laterals originating on 2-year-old canes and then calculating the percent fruit bud.

Measurements. Leaf samples were collected during the first week of August each year and analyzed for nutrients per standard recommendation (Hart et al., 2006). Six recently mature leaves were removed and pooled together from each treatment plant. The samples were oven-dried at 70° C, ground, and analyzed for total N using a combustion analyzer (model CNS-2000; LECO Corp., St. Joseph, MI) and for other macro- and micronutrients by inductively coupled plasma-optical emission spectroscopy (Perkin-Elmer Optima 3000, Wellesley, MA) after nitric acid digestion.

Soil samples were collected during the third week of September each year and analyzed for pH, EC, and nutrients. A 2-cm-diameter soil probe (Clements Associates Inc., Newton, IA) was used to collect the soil samples to a depth of 30 cm at distances of 5 and 20 cm from the crown. Each sample was divided into three depths of 0–10, 10–20, and 20–30 cm. The samples were air-dried at 48°C, ground to pass through a 2-mm sieve, and measured for pH and EC following a 1:2 soil:water (w/w) method (Jackson, 1958; Jones, 2001). Soil organic matter was measured using Loss-On-Ignition at 360 ºC (Nelson and Sommers, 1996). Soil NO_3^--N and NH_4^+-N were determined using automated colorimetric methods after extraction with 1 M KCl

(Dahnke, 1990), extractable soil P was determined using the Bray I method, and K, Ca, Mg, S, Fe, B, Cu, Mn, and Zn were determined using the Mehlich 3 method (Mehlich, 1984).

Soil solution for monitoring EC was collected once a month from May to August in the narrow and wide treatments fertigated only with urea. Mini-lysimeters (Rhizon Soil Moisture Samplers, Eijkelkamp Agrisearch Equipment, The Netherlands) were constructed with porous plastic with 0.15 micron pore size. They were 2.5-mm diameter and 10-cm in length, wire reinforced and were installed in mid-April of 2012. The soil was cut parallel and perpendicular to the row at a distance of 10 cm from the plant. Nine mini-lysimeters were installed per plot and inserted horizontally in the soil at 10, 20, and 30 cm of soil depth (in a straight line below the plant), while 3 more mini-lysimeters on either side of the planting bed, but at 20 cm from the plants (i.e. right below the drip line in the wide system) and aligned with the ones located below the plant (10, 20, and 30 cm). The soil that was removed carefully placed back to cover the hole, allowing only the tubing from the mini-lysimeter to emerge from the planting bed for solution collection. Soil solution collection was done by making a vacuum with a 20-ml syringe connected to each mini-lysimeter. The vacuum was done ≈12 hours after a fertigation event was finished. The vacuum was left overnight and approximately 5-10 mL of soil solution per mini-lysimeter were extracted in each collection.

One plant was randomly selected from each plot and excavated in Oct. 2011 and Oct. 2012 (prior to leaf senescence). First, the leaves were removed from the plants and collected into paper bags. Then, the soil was cut parallel and perpendicular to the row at a distance of 30 cm from each side of the plant to a depth of 40 cm. The plants were lifted with a lever chain hoist and placed onto a washing station. Roots were gently washed free of soil using a low-pressure washer, and the plant was divided into new shoots, woody canes (≥ 2-year-old wood), and the crown and roots. Each plant part, including the leaves, was oven-dried at 70°C to a constant weight. It was difficult to differentiate the crown from the roots in the young plants, and therefore, the crown was included as part of the root dry weight.

Fruit were hand-picked and weighed from each plot on 18 July and 1 Aug. 2012. A random subsample of 100 berries was weighed to determine the average berry weight in each treatment.

Statistical analysis. Data were analyzed by analysis of variance (ANOVA) using the PROC MIXED procedure in SAS (Version 9.3 software, SAS Institute, Cary, NC). Orthogonal contrasts were used to make independent linear comparisons between treatment groups fertigated by narrow and wide drip lines. To achieve homogeneity of variance in the data, soil EC was log-transformed prior to analysis and back-transformed for presentation. Means were separated at the 0.05 level using the Tukey-Kramer Honestly Significant Difference test.

Results

Plant growth and early fruit production. Most components of plant dry weight were affected by the N fertilizer treatments during the first 2 years after planting (Table 5-1 and Table 5-2). Based on total dry weight, the largest plants among the treatments each year were those fertigated with either one line (using ‘urea only’) or two lines of drip tubing located near the base of the plants (using ‘urea + humic acids’, ‘urea sulfuric acid’, ‘urea only’, or ‘urea + P, and Zn’), while the smallest plants were those fertigated with two drip lines positioned at 20 cm from each side of the row (wide). On average, the plants with wider drip lines had less leaf and woody cane dry weights than those with narrow drip lines during the first year, and less new shoot and woody cane dry weights during the second year after planting. The use of granular fertilizer or polymer-coated urea (PCU) did not improve growth with the wider drip line placement, and geotextile tape was no different than using a single line of drip tubing. Pre-plant and late-season applications of N also had no effect on growth in plants fertigated with ‘urea only’ each year. None of the treatments had any effect on root dry weight, except humic acids, which produced more root dry weight than any other treatment by the end of the second year after planting (Table 5-2).

Yield was similar among many of the treatments during the second year after planting and averaged 0.6 kg/plant (Table 5-2). However, plants fertilized with urea sulfuric acid (narrow) and those fertilized with ‘PCU + liquid urea’ (wide) had a lower yield than several of the treatments, including plants fertigated with ‘urea only’ using wide drip lines, using one drip line or geotextile tape, and plants fertigated using narrow drip lines with: ‘liquid urea + P + Zn’, ‘liquid urea without pre-plant N’, or ‘liquid urea in late-season application’ . The fruit were large in each treatment, averaging 3.0 g/berry (data not shown).

Fruit bud set was measured in both years but was similar among treatments all treatments, ranging from 48% to 56% (data not shown). In addition, no signs of cold injury were observed during the study.

Leaf nutrients. The concentration of many essential nutrients in the leaves were affected by the N fertilizer treatments, including leaf N, P, K, Ca, Mg, S, B, Mn, and Zn during the first year after planting (Table 5-3) and leaf N, P, Ca, Mg, B, Cu, and Mn during the second year after planting (Table 5-4). In general, leaf N and Zn were greater the first year with narrow drip lines than with wide drip lines, while leaf K, Ca, Mg, S, and B were greater the first year and leaf B and Mn were greater the second year with wide drip lines than with narrow drip lines. However, there were a number of exceptions. For example, leaf N concentration averaged 1.75% when PCU was applied prior to fertigation with wide drip lines during the first year after planting, which was greater than the N concentration in six other treatments that year, including the plants fertigated using ‘one drip line’, ‘geotextile tape’, and ‘two narrow drip lines with late-season N applications’. However, leaf N was similar among plants fertigated with urea-sulfuric (1.80%), humic acids (1.71%), or liquid urea ‘only’ (1.67%) which were the highest leaf N during the first year. By the following year, leaf N averaged 1.62% when granular urea was applied prior to fertigation with wide drip lines; however, it was similar to nine of the twelve treatments. Leaf N was lowest in plants fertilized with ‘PCU only’, averaging 1.26%. Leaf nutrients were not affected by pre-plant or late-season applications of N relative to the treatment fertigated with ‘urea only’ each year (Table 5-3 and Table 5-4).

Leaf P concentration was similar when urea was applied through narrow and wide drip lines each year. However, some differences were found among the treatments (Table 5-3 and Table 5-4). In year 1, leaf P concentration was greater with 'urea + humic acids' and geotextile tape than with fertigation with 'urea only' through one or two drip lines, or when using 'granular + liquid urea' or 'PCU only' with wide drip lines. In year 2, leaf P concentration was greater with 'urea + P + Zn' than with 'liquid urea only' applied through two narrow or wide drip lines.

Leaf K and S concentrations were different among treatments in year 1 only (Table 5-3). In general, the leaf concentration of both nutrients was greater with wide drip lines than with narrow lines. Leaf Ca concentration was also greater the first year with 'granular + liquid urea' and 'urea sulfuric acid' than with fertigation with 'urea without pre-plant N'; however, the former were similar to all other treatments (Table 5-4). By the following year, leaf Ca concentration was greater with 'urea + humic acids', 'urea + P and Zn', and 'PCU only' than with 'urea sulfuric acid' and fertigation with one drip line. On the other hand, the concentration of leaf Mg was greater the first year with 'granular + liquid urea' than 'urea + humic acids' or 'urea only' applied through narrow drip lines with or without pre-plant N. By the following year, Mg concentration was greater with 'urea + humic acids', 'urea only' in extended application, and with 'PCU only' than with 'urea only' applied through one drip line.

Among the micronutrients, leaf B concentration was greater with wide drip lines than with narrow drip lines each year (Table 5-3 and Table 5-4). Leaf Mn concentration, on the other hand, was greater with 'urea sulfuric acid' than most other treatments but similar to those with granular fertilizer in year 1, greater with ‘PCU + liquid urea’ and fertigation with ‘urea only’ through wide drip lines than most other treatments, except ‘PCU only’, in year 2.

Soil pH, EC, and organic matter. Soil pH, EC, and organic matter differed when liquid urea was applied through narrow or wide drip lines (

Figure 5-1). In the top 20 cm, soil pH was higher at 5 cm than at 20 cm from the crown when plants were fertigated with narrow drip lines, but higher at 20 cm than at 5 cm from the crown when plants were fertigated with wide drip lines (

Figure 5-1A). Soil pH was negatively correlated to soil EC each year (r^2 = -0.58 in year 1 and -0.63 in year 2, $P < 0.0001$). Therefore, soil EC [1:2 soil:water (w/w)] was lower at 5 cm than at 20 cm from the crown with narrow drip lines, and the opposite was found with wide drip lines (

Figure 5-1B). On the other hand, monitoring of the soil solution during the second year showed that EC started to increase in the root zone early in the season when urea was applied with wide drip lines (Figure 5-2). Maximum accumulation of salts occurred in June and July, when EC increased to nearly 3 $dS{\cdot}m^{-1}$ near the base of the plants and decreased a month later, following fertigation, to < 1.5 $dS{\cdot}m^{-1}$. In contrast, the salts appeared to move away from the root zone with narrow drip lines, and soil solution EC was ≤ 1 $dS{\cdot}m^{-1}$ under the plants during the months with fertigation (Figure 5-2).

Soil organic matter content decreased with soil depth and averaged 5.5% in 2011 and 4.4% in 2012 (

Figure 5-1C). It was also consistently lower at 5 cm than at 20 cm from the crown, in the top 10 cm of soil, with either narrow or wide drip lines the first year and with narrow drip lines the following year.

Soil nutrients. At the end of the first year after planting, NH_4-N concentration in the soil averaged 6 ppm and was similar near or far from the crown with either narrow or wide drip lines (Figure 5-2A). However, the following year, the concentration was four-fold higher at 20 cm than at 5 cm from the crown with wide drip lines (i.e., increased below the emitters), but was similar between the two distances with narrow drip lines. The concentration of NO_3-N, on the other hand, increased with soil depth during the first year, and was greatest under the drip emitters the following year (Figure 5-3B).

The concentration of soil P was similar when urea was applied through narrow and wide drip lines each year (Figure 5-3C) but was lower near the crown at each soil depth with 'urea only' than with 'urea sulfuric acid', 'urea + humic acids', or 'urea + P + Zn' (Table 5-5). In addition, soil P was often higher near the drip emitters. The concentration of SO_4-S increased with distance from the emitter and, therefore, had a lower concentration at 5 cm than at 20 cm from the crown with narrow drip lines and vice versa with wide drip lines (Figure 5-3D). The concentration was also lower at 5 cm from the crown when fertigated with narrow drip lines using 'urea sulfuric acid', 'urea + humic acids', or 'urea + P and Zn (Table 5-5). However, there were a few exceptions in these latter cases where the SO_4^--S concentration was similar at 5 and 20 cm.

Lateral movement of basic cations due to drip system appeared to be more significant at 0–10 cm soil depth and primarily during the second year (Figure 5-3E, 3F, and 3G). At that depth and time, the concentration of soil K was greater near the crown with wide drip lines than with narrow drip lines. In contrast, soil Ca and Mg concentrations tended be lower near the crown with wide drip lines.

The soil concentrations of most micronutrients were unaffected by the placement of the drip lines (Figure 5-4). However, Fe decreased in concentration at a depth of 10–20 cm with narrow drip lines during the first year, while Fe during the second year and Mn in both years increased in concentration near the crown with the wide drip lines at a depth of 0–10 cm. Soil Zn concentration showed a similar pattern to soil P and increased with treatments in which it was applied (i.e., urea + humic acids or urea + P + Zn) and were consistently higher at 5 cm than at 20 cm from the crown, particularly at 0–10 cm (Table 5-5).

Discussion

Early growth of blueberry was greater in the present study when plants were irrigated and fertigated with one or two lines of drip tubing or tape located near their base (crown) than with two lines of drip located at 20 cm from each side crown. A wider drip line placement often encourages greater root development in many crops, including highbush blueberry (Vargas et al., 2015 in press). It may also reduce the risk of developing root diseases such as *Phytophthora* root rot (Yeo, 2014). However, in this study, wider drip lines resulted in lower N concentrations in the leaves and higher concentrations of EC (salts) in the soil solution near the plants.

High salinity in the rhizosphere of salt-sensitive crops, such as blueberry, reduces shoot and root growth, yield and fruit quality (Bryla and Machado, 2011; Grattan and Grieve, 1999). Reduced salinity hazards with fertigation are often associated with efficient displacement of salts to the periphery of the wetted soil volume, reducing salinity in the root zone (Bar-Yusef, 1999). Other studies have shown that fertigation results in lower salt accumulation immediately below the emitters (West et al., 1979). However, mobile nutrients such as NO_3-N and SO_4-S move by mass flow in the soil and tend to accumulate and increase salinity at the wetting front boundaries (Bernstein and Francois, 1973). This study showed that accumulation of ions either near or far from the crown depended on the placement of the drip lines.

Controlled-release polymer-coated urea (PCU) and low rate of granular urea also increased salinity and decreased pH in the root zone compared to different liquid fertilizers applied with narrow drip lines. The PCU used in this study was designed to release the N within 1 to 2 months, depending on temperature and moisture, and therefore probably resulted in high concentrations of soil N due to the short release period.

A number of studies have reported that frequent fertigation with ammonium fertilizers results in acidification immediately below the drip emitters due to nitrification (Haynes and Swift, 1987; Haynes, 1990, Nielsen et al., 1999). However, the results of the present study indicated that soil pH was higher at 5 cm from the emitters than at 20 cm from the emitters. This is probably because urea was used in the present study. Although urea is less acidifying than NH_4-N, it is much more mobile in the soil (Kissel et al., 1998; Havlin et al., 2005). If the urea moved to the edge of the wetting front during fertigation, it would explain why soil pH was higher at the base of the plants with narrow drip lines than with wide drip lines. The opposite would have probably happened if we used an ammonium N source such as liquid ammonium sulfate.

Urea sulfuric acid application and liquid urea (both with the narrow system) produced similar total dry weight in both years. Urea sulfuric acid may be of great benefit in blueberry due to acidifying effect of this fertilizer source (Havlin et al., 2005). Soil pH was lower with urea sulfuric acid and humic acids in the first 0.20 m of soil depth compared to liquid urea. There was also increased soil P near the crown and in some occasions, K, Fe, and B, depending on the year. The acidifying effects of these fertilizers also may have resulted in greater leaf N, P, Ca, Mg, S, and Mn concentrations during the first year after planting. Elkins et al. (2002) found that drip applied urea sulfuric acid reduced soil pH by one unit (compared to the control) directly under the drip emitters and resulted in increased availability of soil P, Fe, and Zn. Even though plant dry weight was similar between fertigation with urea and urea sulfuric acid, the latter resulted in better plant nutrition. For example, during the first year after planting, plants fertilized with urea sulfuric acid had the highest leaf N concentration. In contrast, leaf P concentration was below the recommended sufficiency level for highbush blueberry (Hart et al., 2006) during the second year in plants fertigated by urea. Thus, the use of urea sulfuric acid may be more beneficial over the long term or in high pH soils.

Soil pH was also lower near the crown with urea + humic acids than with urea only or urea + P + Zn. Not surprisingly, the concentration of soil P and Zn were also greater near the crown with humic acids and P and Zn than with urea only. The fact that leaf nutrients were similar among these treatments suggests that the positive effect of humic acids on root growth may have been attributed to the humic acids component. The effects of humic acids on plant growth have been inconsistent (Rose et al., 2014) partly due to the wide range of physiochemical properties from different sources and methods of extraction (Senesi, 1994). Regardless of the complexity in chemical structure, humic acids have been shown to have direct and indirect effects on plant growth. Direct effects are related to better nutrient availability, increased CEC, absorption of small molecular weight molecules, and hormone-like effects, while indirect effects are related to improved soil structure such as soil aggregation (Allison, 1973; Chen and Aviad, 1990; Rose et al., 2014). Akanani et al. (1990) reported that humic acid reduced urea hydrolysis and nitrification. The association of soluble phosphate with humic acids reduces its binding and precipitation in soil, allowing for greater plant uptake (Alvarez et al., 2004; Hua et al., 2008). However, in our study this cannot be assumed completely since P was applied with the humic acid program, and leaf P was similar between the humic acids and P + Zn treatments. Hartz and Botomms (2010) found that humic acids were generally ineffective at improving plant growth in lettuce (*Lactuca sativae* L.) and tomato (*Lycopersicon esculentum* Mill.). They attributed the lack of response to the small rate applied in commercial recommendations (≈5 kg·ha^{-1}). However, our study is in agreement with Chen and Aviad (1990) and Chen at al., (2004) who suggested that under adequate conditions of soil nutrients, humic acids consistently show positive effects on plant growth, and normally, stimulation of root growth is more apparent than stimulation of shoot growth. In addition, humic acids may improve micronutrient uptake by chelation of metal cations such as Fe and Zn, and small fractions of low weight molecules may be absorbed by the roots by increasing cell membrane permeability and thus nutrient use efficiency. It has been suggested that these compounds may also have hormone-like activity within the plants (Seyedbagheri and Torell, 2001).

Blueberry plants are known to respond positively to organic matter when grown in mineral soils, including sawdust, pine bark, and peat moss, although the exact mechanism responsible for the benefit is still unclear (Clark and Moore, 1991; Lareau, 1989; White, 2006). The benefit may be attributed to better drainage, soil aeration, and improved weed control when organic matter is incorporated prior to planting (Sullivan et al., 2014). Organic matter is commonly added in blueberry production as Douglas-fir sawdust, and ≈3-3.5 kg of N·m^{-3} is typically incorporated to overcome N immobilization (Hart et al., 2006; Julian et al., 2011; White, 2006). In this study, Douglas-fir sawdust was incorporated before planting at a rate of ≈350 m^{3}·ha^{-1} with N (105 kg·ha^{-1}) or with no added N, to evaluate the impact of pre-plant N on plant growth and leaf nutrients. The results showed that pre-plant N had no effect on total dry weight during the first two years after planting compared to the absence of pre-plant N (Table 5-1 and Table 5-2). Leaf N concentration was also similar with or without pre-plant N.

Late-season applications of N fertilizer had no effect on plant growth, fruit bud set, or early fruit production in the present study. In this study, same N rate (100 $kg \cdot ha^{-1}$) were applied during the late-season treatment (April to September) and the standard period (April to July) and therefore the amount of N fertigated per week was lower in the late-season treatment. However, if the same amount of N were applied per week and extended until September (in the late-season treatment) may result in late growth reducing fruit bud set and increasing the risk cold damage. Late application of N fertilizer promotes late flushes of shoot growth (Bañados, 2006), reducing bud set (B.C. Strik, personal observation) and that are highly susceptible to winter injury (Caruso and Ramsdell, 1995). Nonetheless, more work is needed to determine the relationship between the timing of N fertilizer applications and the impact on fruit bud set and winter freeze tolerance in highbush blueberry.

Conclusions

Total blueberry plant growth was best with fertigation with narrow placement than wide placement of drip lines. Narrow placement improved soil condition resulting in lower salinity in the rhizosphere compared to wide drip placement. Plants with wide drip lines had less leaf and woody cane dry weight than with the narrow drip lines by the second year. Humic acids improved plant dry weight compared to treatments with wide drip lines in both years and root weight was greater than any other treatment by the second year. While the use of urea-sulfuric acid also improved growth, total plant growth was only similar to urea fertigation. Benefits of humic acids and urea-sulfuric acid may be attributed to lower soil pH (blueberry is best adapted to low pH) compared to fertigation with urea ‘only’ or N+P + Zn (narrow). However, the increase in root growth by humic acids is not well understood. Some possible explanations may include improved root plasma membrane permeability (increased nutrient use efficiency) and hormone-like effects.

The application of granular fertilizer in small rate or PCU applied around plants did not improve plant growth when drip lines were placed away from the crown. While the use of the geotextile tape was not beneficial compared to one drip line.

On the other hand, absence of pre-plant N incorporation did not have negative effect on total plant growth, and therefore may not be necessary when N is applied by fertigation. Although, extended N application (April to September) resulted in similar plant growth compared to fertigation with urea in the standard period (April to July), extended N application at higher N rate than the used in this study may reduce flower bud initiation, increase the risk of cold damage over the winter and reduce yield the following season.

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Tables and Figures

Table 5-1 Dry weight and yield of 'Draper' blueberry plants following the first year after planting (2011) in western Oregon.

Drip system / N source	N rate (kg·ha^{-1})	Application date(s)	Dry wt (g/plant)				
			Leaves	New shoots	Woody canes	Roots	Total
Two drip lines (narrow), urea (liq.) + humic acids (liq.)	100	April–July	106 a^{z}	57 a	60 a	68	291 a
Two drip lines (narrow), urea sulfuric acid (liq.)	100	April–July	98 a	52 a	44 ab	63	258 ab
Two drip lines (narrow), urea (liq.)	100	April–July	82 ab	40 abc	47 ab	65	234 abc
Two drip lines (narrow), urea (liq.) + P and Zn (liq.)	100	April–July	79 ab	39 abc	45 ab	65	228 abc
One drip line, urea (liq.)	100	April–July	64 bc	36 abc	50 ab	64	214 abcd
Two drip lines (narrow), urea (liq.) w/out pre-plant N	100	April–July	55 bc	37 abc	43 ab	67	202 bcd
Two drip lines (narrow), urea (liq.) w/late-season N	100	April–September	66 bc	37 abc	37 b	56	195 bcd
Geotextile tape, urea (liq.)	100	April–July	51 bc	44 ab	35 b	58	188 bcd
Two drip lines (wide), urea (gran. + liq.)	10/10 + 80	April/May + June–July	52 bc	22 c	39 b	58	170 cd
Two drip lines (wide), PCU + urea (liq.)	60 + 40	April + June–July	54 bc	29 bc	35 b	48	166 cd
Two drip lines (wide), PCU	60	April	45 c	26 bc	35 b	52	157 cd
Two drip lines (wide), urea (liq.)	100	April–July	39 c	30 bc	31 b	49	148 d
Significance			***	***	***	NS	***
Contrast							
Two drip lines (narrow) vs. two drip lines (wide)			***	NS	**	NS	**

^{z}Means (n = 5) followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey's honestly significant difference test.

$^{NS, **, ***}$Nonsignificant or significant $P \leq 0.01$ or 0.001, respectively.

Table 5-2 Dry weight and yield of ‘Draper’ blueberry plants following the second year after planting (2012) in western Oregon.

Drip system / N source	N rate (kg·ha^{-1})	Application date(s)	Dry wt (g/plant) Leaves	New shoots	Woody canes	Roots	Total	Yield (kg/plant)
Two drip lines (narrow), urea (liq.) + humic acids (liq.)	100	April–July	271 a[z]	158 abc	222 a	350 a	1000 a	0.64 ab
Two drip lines (narrow), urea sulfuric acid (liq.)	100	April–July	252 ab	131 b-e	205 ab	219 b	807 abc	0.48 b
Two drip lines (narrow), urea (liq.)	100	April–July	271 a	161 ab	192 ab	241 b	864 ab	0.65 ab
Two drip lines (narrow), urea (liq.) + P and Zn (liq.)	100	April–July	236 abc	143 a-e	182 ab	236 b	797 abc	0.67 a
One drip line, urea (liq.)	100	April–July	226 abc	177 a	218 ab	227 b	847 ab	0.67 a
Two drip lines (narrow), urea (liq.) w/out pre-plant N	100	April–July	228 abc	152 a-d	200 ab	221 b	802 abc	0.72 a
Two drip lines (narrow), urea (liq.) w/late-season N	100	April–September	217 abc	127 b-e	223 a	216 b	783 abc	0.68 a
Geotextile tape, urea (liq.)	100	April–July	235 abc	129 b-e	228 a	216 b	808 abc	0.66 a
Two drip lines (wide), urea (gran. + liq.)	10/10 + 80	April/May + June–July	185 bc	96 b	159 b	212 b	652 bc	0.70 a
Two drip lines (wide), PCU + urea (liq.)	60 + 40	April + June–July	222 abc	117 b-e	159 b	200 b	698 bc	0.37 c
Two drip lines (wide), PCU	60	April	168 c	104 ed	164 b	201 b	637 c	0.62 ab
Two drip lines (wide), urea (liq.)	100	April–July	218 abc	110 e	168 ab	224 b	720 bc	0.55 ab
Significance			***	**	***	**	***	0.64 ab
Contrast								
Two drip lines (narrow) vs. two drip lines (wide)			NS	*	**	NS	*	NS

[z]Means (n = 5) followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey’s honestly significant difference test.

NS, *, **, ***Nonsignificant or significant $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 5-3 Leaf nutrient concentrations in 'Draper' blueberry during the first year after planting (2011) in western Oregon.

	N rate	Application	Macronutrients (%)						Micronutrients (ppm)				
Drip system / N source	(kg·ha^{-1})	date(s)	N	P	K	Ca	Mg	S	Fe	B	Cu	Mn	Zn
Two drip lines (narrow), urea (liq.) + humic acids (liq.)	100	April–July	1.71 abc[z]	0.12 a	0.53 d	0.65 ab	0.18 bc	0.17 d	162	36 bc	2.5	232 bcd	12.7 a
Two drip lines (narrow), urea sulfuric acid (liq.)	100	April–July	1.80 a	0.12 ab	0.57 bcd	0.70 a	0.22 ab	0.29 a	155	36 bc	3.0	329 a	11.3 abc
Two drip lines (narrow), urea (liq.)	100	April–July	1.67 abc	0.11 b	0.54 cd	0.59 ab	0.17 c	0.17 d	143	42 bc	2.8	213 bcd	10.7 bc
Two drip lines (narrow), urea (liq.) + P and Zn (liq.)	100	April–July	1.61 bcd	0.12 ab	0.56 bcd	0.65 ab	0.19 abc	0.19 cd	153	37 bc	2.5	177 d	11.0 abc
One drip line, urea (liq.)	100	April–July	1.57 cd	0.11 b	0.56 bcd	0.63 ab	0.19 abc	0.18 cd	140	31 c[z]	2.5	211 bcd	10.9 abc
Two drip lines (narrow), urea (liq.) w/out pre-plant N	100	April–July	1.61 bcd	0.11 b	0.54 cd	0.57 b	0.17 c	0.16 d	180	32 c	2.5	187 d	9.8 c
Two drip lines (narrow), urea (liq.) w/late-season N	100	April–September	1.55 cd	0.11 ab	0.57 bcd	0.60 ab	0.18 abc	0.19 bcd	159	33 c	2.6	184 d	10.3 bc
Geotextile tape, urea (liq.)	100	April–July	1.58 cd	0.12 a	0.64 abc	0.67 ab	0.20 abc	0.24 abc	153	45 bc	2.8	237 bcd	11.1 abc
Two drip lines (wide), urea (gran. + liq.)	10/10 + 80	April/May + June–July	1.46 d	0.11 b	0.69 a	0.72 a	0.22 a	0.27 a	176	45 bc	2.8	281 abc	12.1 ab
Two drip lines (wide), PCU + urea (liq.)	60 + 40	April + June–July	1.75 ab	0.11 ab	0.64 abc	0.68 ab	0.21 abc	0.26 a	154	51 ab	2.7	295 ab	10.4 bc
Two drip lines (wide), PCU	60	April	1.55 cd	0.11 b	0.66 ab	0.65 ab	0.21 abc	0.25 ab	144	47 bc	2.6	244 abcd	9.6 c
Two drip lines (wide), urea (liq.)	100	April–July	1.50 d	0.12 ab	0.65 ab	0.67 ab	0.21 ab	0.29 a	158	65 a	2.4	200 cd	9.4 c
Significance			***	***	***	**	***	***	NS	***	NS	***	***
Contrast													
Two drip lines (narrow) vs. two drip lines (wide)			**	***	***	NS	**	***	NS	***	NS	NS	*

[z]Means (n = 5) followed by a different letter within a column are significantly different at $P \le 0.05$, according to Tukey's honestly significance difference test.

NS, *, **, ***Nonsignificant or significant $P \le 0.05$, 0.01, or 0.001, respectively.

Table 5-4 Leaf nutrient concentrations in 'Draper' blueberry during the second year after planting (2012) in western Oregon.

	N rate	Application	Macronutrients (%)						Micronutrients (ppm)				
Drip system / N source	(kg·ha^{-1})	date(s)	N	P	K	Ca	Mg	S	Fe	B	Cu	Mn	Zn
Two drip lines (narrow), urea (liq.) + humic acids (liq.)	100	April–July	1.61 a	0.10 ab	0.54	0.74 a	0.19 a	0.14	286	50 ab	3.9 ab	357 ab	7.4
Two drip lines (narrow), urea sulfuric acid (liq.)	100	April–July	1.56 a	0.10 ab	0.47	0.61 bc	0.17 ab	0.13	316	35 c	3.2 ab	299 d	8.1
Two drip lines (narrow), urea (liq.)	100	April–July	1.50 ab	0.09 b	0.50	0.67 abc	0.17 ab	0.14	338	43 bc	2.7 b	306 bc	7.8
Two drip lines (narrow), urea (liq.) + P and Zn (liq.)	100	April–July	1.57 a	0.11 a	0.49	0.74 a	0.18 ab	0.15	346	45 ab	3.3 ab	334 b	7.9
One drip line, urea (liq.)	100	April–July	1.48 ab	0.10 ab	0.46	0.60 c	0.15 b	0.13	329	36 c	2.9 ab	301 c	7.9
Two drip lines (narrow), urea (liq.) w/out pre-plant N	100	April–July	1.48 ab	0.10 ab	0.49	0.66 abc	0 .18 ab	0.13	383	43 b	3.5 ab	316 c	7.9
Two drip lines (narrow), urea (liq.) w/late-season N	100	April–September	1.40 bc	0.10 ab	0.49	0.68 abc	0.19 a	0.14	246	39 b	3.2 ab	272 d	8.2
Geotextile tape, urea (liq.)	100	April–July	1.48 ab	0.09 ab	0.51	0.65 abc	0.16 ab	0.14	326	43 bc	3.5 ab	337 b	7.9
Two drip lines (wide), urea (gran. + liq.)	10/10 + 80	April/May + June–July	1.62 a	0.11 ab	0.49	0.69 abc	0.18 ab	0.14	240	49 ab	3.0 ab	318 c	7.6
Two drip lines (wide), PCU + urea (liq.)	60 + 40	April + June–July	1.56 a	0.11 ab	0.50	0.74 ab	0.18 ab	0.16	287	53 a	3.7 ab	421 a	8.1
Two drip lines (wide), PCU	60	April	1.26 c	0.10 ab	0.48	0.76 a	0.19 a	0.15	309	54 a	3.8 a	387 ab	7.9
Two drip lines (wide), urea (liq.)	100	April–July	1.52 ab	0.09 b	0.49	0.66 abc	0.16 ab	0.14	341	53 a	3.1 ab	427 a	7.8
Significance			***	*	NS	***	**	NS	NS	*	*	*	NS
Contrast													
Two drip lines (narrow) vs. two drip lines (wide)			NS	NS	NS	NS	NS	NS	NS	*	NS	*	NS

[z]Means (n = 5) followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey's honestly significance difference test.

NS, *, **, ***Nonsignificant or significant $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 5-5 Effects of different N sources on soil pH and soil nutrients in a field of 'Draper' blueberry during the first 2 years after planting (2011–2012) in western Oregon.

Soil depth / liquid N source(s)[z]	Soil pH				Soil P ($mg\cdot kg^{-1}$)				Soil S-SO_4 ($mg\cdot kg^{-1}$)				Soil Zn ($mg\cdot kg^{-1}$)			
	2011		2012		2011		2012		2011		2012		2011		2012	
	5 cm	20 cm	5 cm	20 cm	5 cm	20 cm	5 cm	20 cm	5 cm	20 cm	5 cm	20 cm	5 cm	20 cm	5 cm	20 cm
0–10 cm																
Urea	4.7 b[y]	4.9	6.2 a A	4.7 B	13 b	14	14 b	14	44	86	11 b	73	3.4 b	4.2	3.9 b	3.3
Urea sulfuric acid	4.7 b	4.8	5.2 b A	4.6 B	44 a A	13 B	23 b	17	65 B	152 A	193 a	134	3.3 b	3.9	3.6 b	4.0
Urea + humic acids	4.8 b	4.8	5.4 b A	4.6 B	23 b	12	62 a A	14 B	115	105	51 b B	173 A	4.8 ab A	3.1 B	24.7 a A	4.1 B
Urea + P and Zn	5.6 a A	4.7 B	6.0 a A	4.7 B	46 a A	13 B	69 a A	14 B	69 B	129 A	11 b B	101 B	5.6 a A	3.6 B	9.1 b A	3.3 B
Significance	***	NS	***	NS	***	NS	***	NS	NS	NS	***	NS	**	NS	***	NS
10–20 cm																
Urea	4.9	5.0	6.1 a A	5.5 B	15 b	14	14 b	14	31	72 b	16	21	2.9 b	3.1	2.2	2.9
Urea sulfuric acid	4.9	4.9	5.2 b	5.4	30 ab A	14 B	21 b	16	28 B	144 a A	20	25	3.1 ab	3.3	3.6	3.1
Urea + humic acids	4.9	4.8	5.5 b	5.3	25 ab	12	40 a A	16 B	50 B	165 a A	15	42	3.4 ab	3.1	5.7	3.4
Urea + P and Zn	5.0	4.9	6.0 a	5.6	37 a A	16 B	53 a A	17 B	31 B	102 ab A	10	17	4.7 a A	2.9 B	6.3	3.1
Significance	NS	NS	***	NS	*	NS	***	NS	NS	*	NS	NS	*	NS	NS	NS
20–30 cm																
Urea	5.4 a	5.7	6.2 a	6.1	16	13	14	14	18	28	14	22	2.8	2.5	2.4	2.2
Urea sulfuric acid	5.0 b B	5.6 A	5.4 b	5.6	26	16	17	17	25	67	25	24	3.1	3.0	2.6	2.7
Urea + humic acids	5.5 a	5.6	6.0 ab	5.9	33 A	14 B	17	15	69	59	14	27	3.0	2.9	2.9	2.2
Urea + P and Zn	5.3 ab	5.5	6.0 ab	6.0	35 A	15 B	20	18	16	39	12	15	3.4	2.7	3.2	2.7
Significance	**	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

[z]Each treatment was fertigated using two drip lines located near the base of the plants. Soil EC, organic matter content, NH_4-N, NO_3-N, K, Ca, Mg, Fe, B, Cu, and Mn, were similar among the treatments at each depth and year.

[z]Means (n = 5) followed by a different letter within a column are significantly different at $P \leq 0.05$, according to Tukey's honestly significant test.

NS, *, **, ***Nonsignificant or significant $P \leq 0.05$, 0.01, or 0.001, respectively.

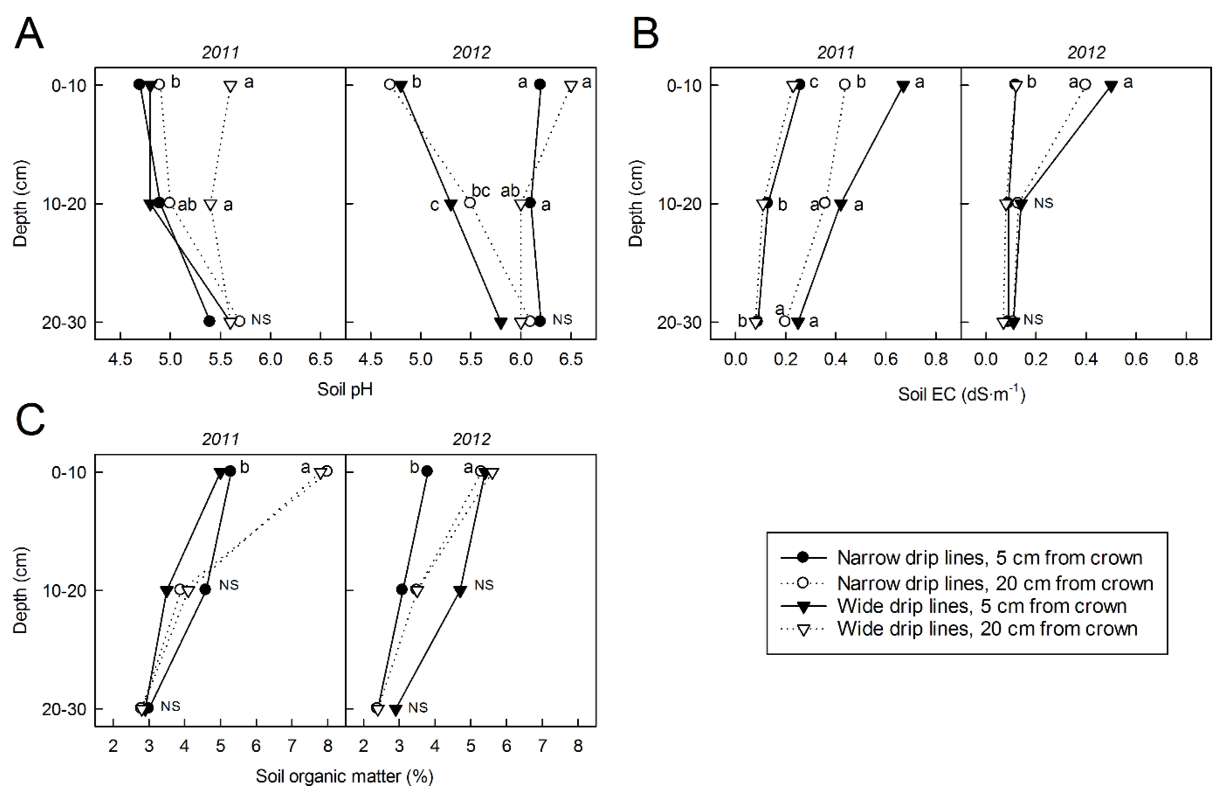

Figure 5-1 Soil pH, EC, and soil organic matter during the first two years after planting (2011–2012) in plots of 'Draper' blueberry fertigated with urea through two drip lines installed at either 5 cm (narrow) or 20 cm (wide) from each side of the plants. Soil was sampled in late September each year in 10-cm depth increments from 0–30 cm at a distance of 5 cm and 20 cm from the crown.

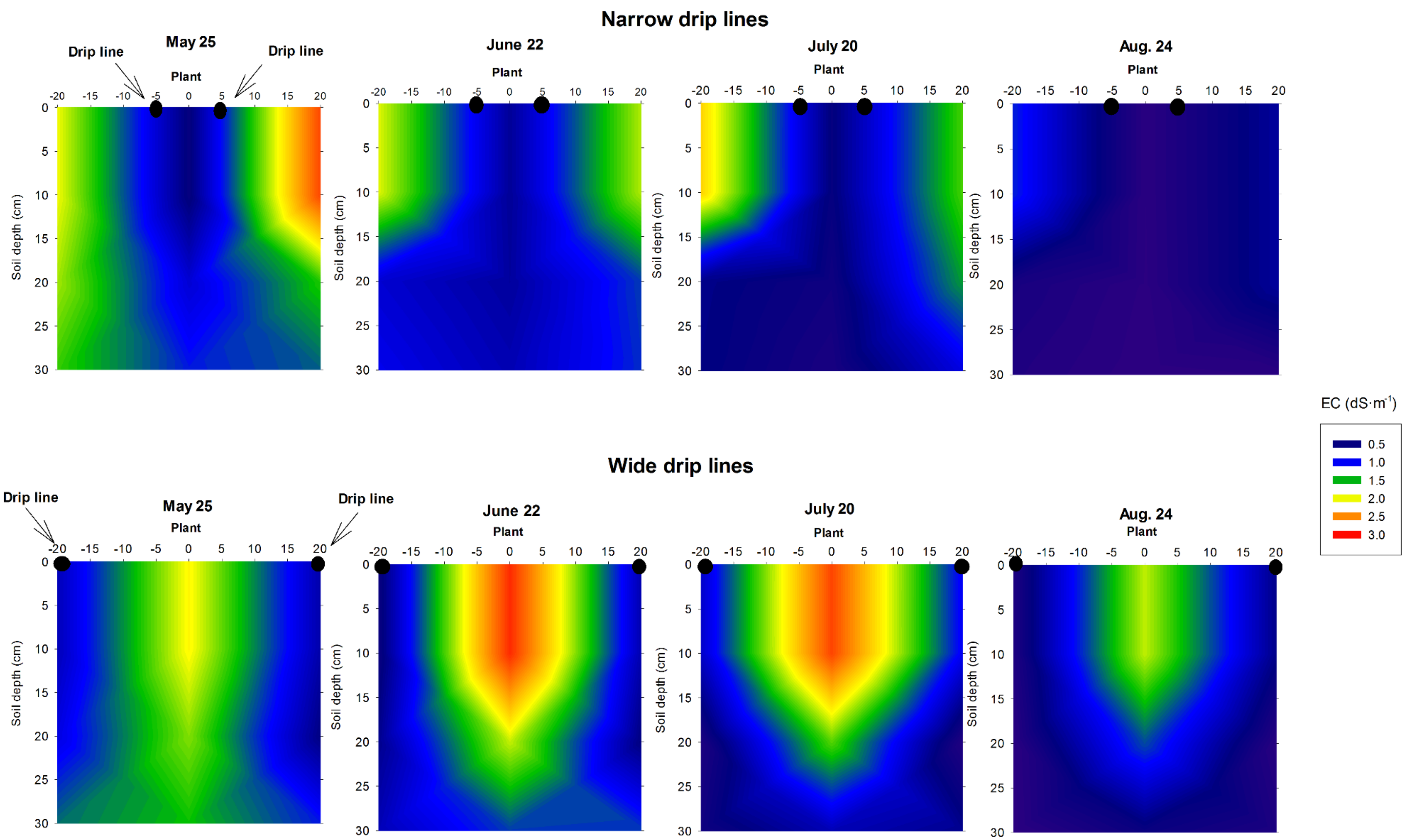

Figure 5-2. Soil solution EC (dS·m-1) during the second year after planting (2012) in plots of 'Draper' blueberry fertigated with urea through two drip lines installed at either 5 cm (narrow) or 20 cm (wide) from each side of the plants.

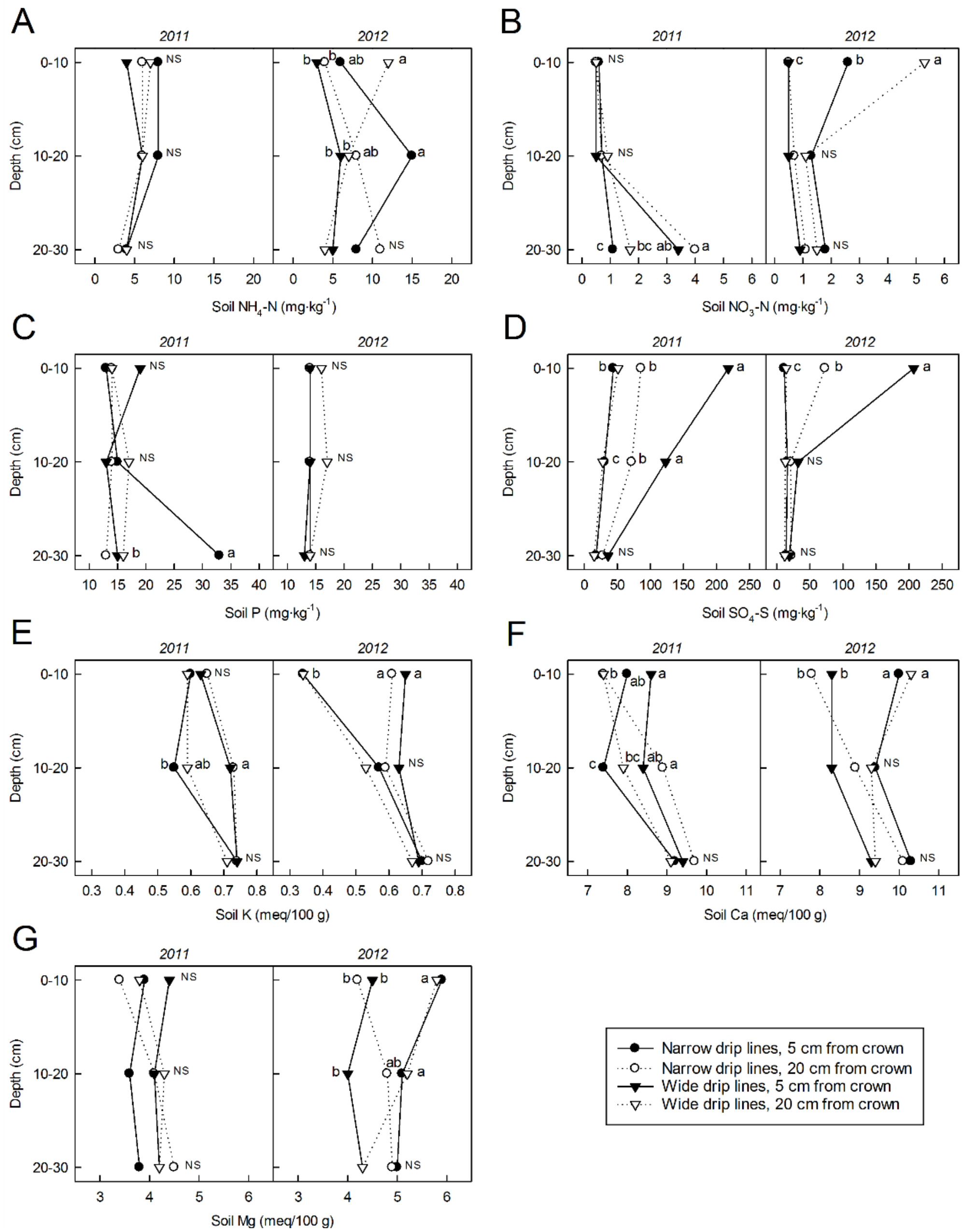

Figure 5-3 Soil NH4, NO3, P, SO4-S, K, Ca, and Mg during the first two years after planting (2011–2012) in plots of 'Draper' blueberry fertigated with urea through two drip lines installed at either 5 cm (narrow) or 20 cm (wide) from each side of the plants. Soil was sampled in late September each year in 10-cm depth increments from 0–30 cm at a distance of 5 cm and 20 cm from the crown.

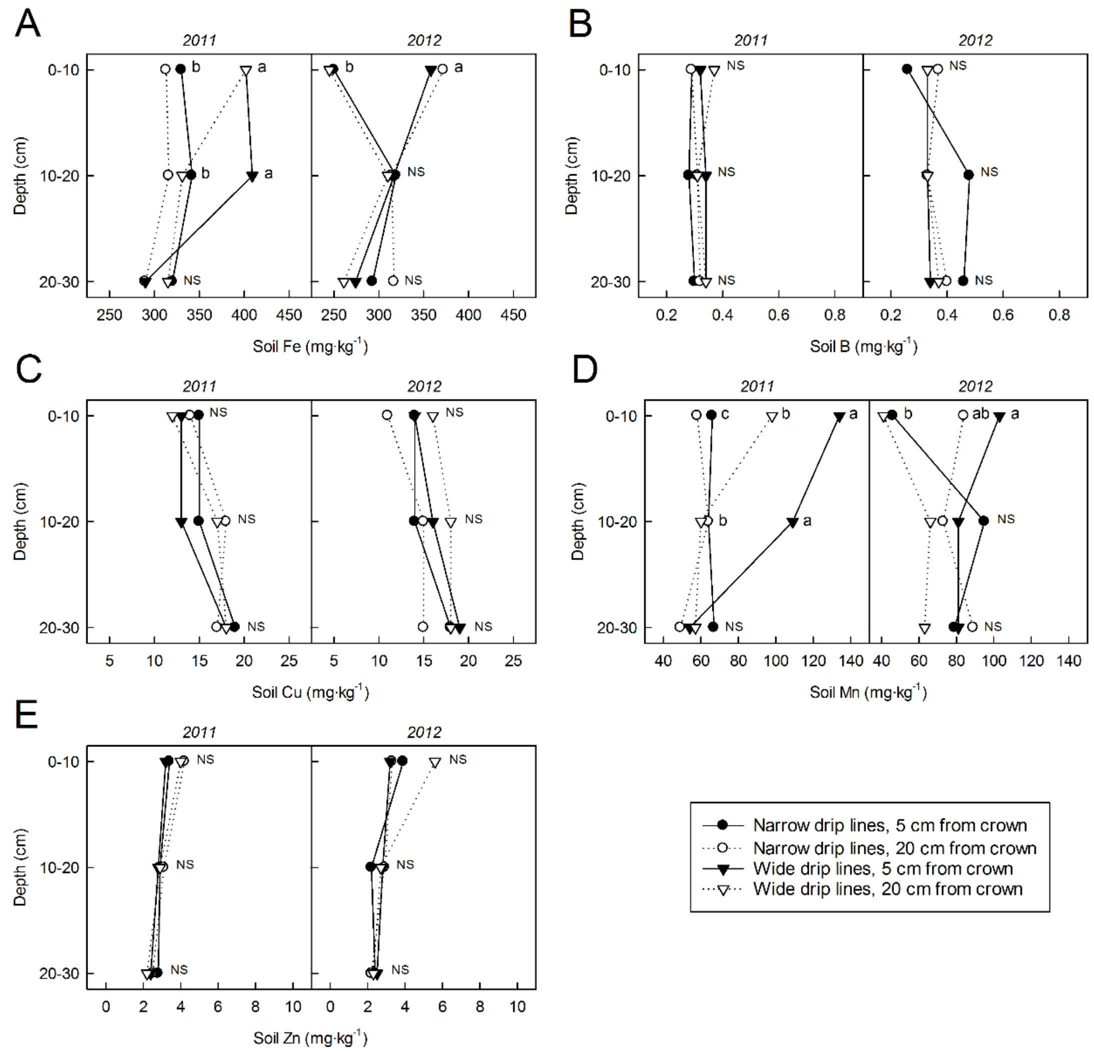

Figure 5-4 Soil NH4, NO3, P, SO4-S, K, Ca, and Mg during the first two years after planting (2011–2012) in plots of 'Draper' blueberry fertigated with urea through two drip lines installed at either 5 cm (narrow) or 20 cm (wide) from each side of the plants. Soil was sampled in late September each year in 10-cm depth increments from 0–30 cm at a distance of 5 cm and 20 cm from the crown.

Chapter 6 – General Conclusions

Oscar Vargas

This work showed that highbush blueberry is sensitive to high nutrient concentration in the root zone. Plant growth was reduced not only by the application of granular fertilizers but also with fertigation when nutrients displace toward the root zone. The effects on plant growth may be attributed to osmotic stress, nutrient imbalances and toxicities. Nutrient application in blueberry production was demonstrated to be necessary to optimize, root, shoot growth, and yield. The delivery of nutrients in small but continuous amounts provided by fertigation appeared to benefit the conditions for root development (decreases the possibility of nutrient excess) and thus overall plant performance. Thus, the implications of this work highlights the advantage of fertigation over granular application and provides evidence that blueberry nutrition is different than most other fruit crops. In the first study fertigation resulted in more plant growth and yield than granular applications of N fertilizers over 5 years of fruit production. Even though plant growth may increase with high N rates, particularly with fertigation, high N rates did not improve yield in any year and affected berry weight during the first 3 years of production. Therefore, 67–93 $kg\cdot ha^{-1}$ N was adequate to maximize fruit production. These rates are lower than the 100–160 $kg\cdot ha^{-1}$ N typically recommended in commercial blueberry production. Ammonium sulfate resulted in higher leaf N concentrations, as well as lower soil pH, than urea, and increased cumulative yield by 10% when the fertilizers were applied by fertigation. However, ammonium sulfate also increased soil EC more than urea and resulted in lower yields during the first 2 years than any other treatment when applied as a granular fertilizer. Thus, urea may be preferable initially when using granular fertilizers.

The root study showed that fertigation and granular application in blueberry had strong effect on root production, root lifespan and root turnover of blueberry. The study provided better understanding of why fertigation results in improved conditions around roots. In particular, fertigation clearly reduced the number of roots produced and increased root lifespan. The implications of fertigation over granular application relies on the capability of plants to produce more efficient roots in a low stress soil environment and, thus keep them alive for a longer time. This is translated into improved shoot production due to lower C cost to produce roots. In addition, these findings show the importance of high root production periods over the growing season and may provide benefits for best fertilization guidelines in blueberry. Thus, proper N application should increase throughout the season as the number of roots increases until the first peak. In addition, peaks root of production may be a starting point for further research to evaluate the application of other nutrients since fertigation has the advantage and flexibility of applying soluble nutrients to match plant needs and in periods of high root activity.

In the establishment of different cultivars, less N was needed to produce 1 kg of fruit with (100 $kg{\cdot}ha^{-1}$ N) compared to higher N rates and alternative methods. Thus yield was also most efficient when the plants were fertigated by drip at the lower N rate (100 $kg{\cdot}ha^{-1}$ N). While geotextile tape was also effective, particularly during the first year after planting, it was more costly and produced more-or-less the same amount growth and yield as drip the following 2 years. Geotextile tape also increased the incidence of root rot in ‘Draper’. Fertigation with microsprinklers, on the other hand, showed lower N efficiency and resulted in reduced plant growth, yield and berry quality (white deposits on the berries) in each cultivar. Installing the microsprinklers at a lower height may help avoid these problems. While drip was clearly the best system for fertigation of blueberry in the present study, the alternative systems could have advantages in sandier soils where lateral movement of water and nutrients is more limited. Therefore, further testing of these systems in other soil types with low water holding capacity is needed.

The drip line placement study showed that total blueberry plant growth was best with fertigation and narrow placement of drip lines rather than wide placement. Narrow placement improved soil conditions and resulted in lower salinity in the rhizosphere compared to wide drip placement due to displacement of nutrients away from the rhizosphere. Plants with wide drip lines had less leaf and woody cane dry weight than with the narrow drip lines by the second year. Similarly, the use of urea-sulfuric acid also improved growth compared to wide system treatments, but was only similar to urea fertigation with narrow system. The inclusion of humic acids showed a positive impact on plant dry weight compared to treatments with wide drip lines in both years. In addition, root weight increased by ≈60% when compared to any other treatment. However, the increase in root growth by humic acids is not well understood yet. Some possible explanations may include improved root plasma membrane permeability (increased nutrient use efficiency) and hormone-like effects. The application of granular urea in small rates or PCU applied around plants did not improve plant growth when drip lines were placed away from the crown, and again granular application resulted poor plant growth due to in increased salinity. While the use of the geotextile tape was not beneficial compared to one drip line. On the other hand, absence of pre-plant N incorporation did not have negative effect on total plant growth, and therefore may not be necessary when N is applied by fertigation. Although, extended N application (April-Sept.) resulted in similar plant growth compared to fertigation with urea in the standard period (April-July), extended N application may reduce flower bud initiation, increase the risk of cold damage over the winter and reduce yield the following season.

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