Organic Production Systems in Northern Highbush Blueberry: II. Impact of Planting Method, Cultivar, Fertilizer, and Mulch on Leaf and Soil Nutrient Concentrations and Relationships with Yield from Planting through Maturity

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Abstract. The impact of various production systems on leaf nutrient concentration and soil organic matter, pH, and nutrient status was evaluated from the first growing season (2007) through maturity (2016) in a certified organic planting of northern highbush blueberry (*Vaccinium corymbosum* L.). Treatments included planting method (on raised beds or flat ground), fertilizer source (granular feather meal or fish solubles) and rate (“low” and “high” rates of 29 and 57 kg·ha⁻¹ N, respectively, during establishment, increased incrementally as the planting matured to 73 and 140 kg·ha⁻¹ N, respectively), mulch [sawdust, yard-debris compost topped with sawdust (compost + sawdust), or black, woven polyethylene groundcover (weed mat)], and cultivar (Duke or Liberty). Mulches were replenished, as needed, and weeds were controlled throughout the study. The impacts of year, planting method, fertilizer, mulch, and cultivar on leaf and soil nutrient levels over this 10-year study were complex with many interactions among treatments. Soil pH remained within the recommended range for all treatments. Plants fertilized with fish solubles had higher leaf N, P, and K concentrations than those fertilized with feather meal, particularly at the high N rate in both cultivars. By contrast, fertilization with feather meal increased leaf Ca. Compost + sawdust added a cumulative (2007–16) total of 2274, 400, 961, and 2744 kg·ha⁻¹ of N, P, K, and Ca, respectively, over the use of sawdust alone, and increased the concentration of P, K (as much as 90%), Ca, and Mg in the soil relative to other mulches. Soil organic matter content averaged 4.1% under compost + sawdust, 3.3% under sawdust, and 2.9% under weed mat, averaged over the last 5 years. Mulching with weed mat or compost + sawdust increased leaf K compared with sawdust in both cultivars, regardless of fertilizer treatment. Leaf Ca, on the other hand, was highest with sawdust and tended to be lowest with weed mat in both cultivars. Soil nutrient levels were not consistently correlated with leaf nutrient concentrations, other than between soil NO₃-N and leaf N (5 years) and between soil and leaf K (4 years). On average, raised beds resulted in higher concentrations of N, P, K, Fe, and Al and lower concentrations of Ca, Mg, and B in the leaves than planting on flat ground. Furthermore, concentrations of N and Ca in recent fully-expanded leaves at standard sampling time was higher in young plants than in mature plants in both cultivars, whereas the opposite was found for leaf P. In ‘Duke’, yield was positively correlated with leaf Ca in 8 out of 9 years and negatively correlated with leaf K and P in 5 and 6 years, respectively. Leaf Ca and Mg were also negatively correlated with leaf K in most years for both cultivars, as was leaf N. Although leaf N concentration was higher with added compost, regardless of fertilizer source in ‘Duke’, and when fertilized with feather meal in ‘Liberty’, this was not correlated with yield. High N rates increased leaf N concentration, but did not result in greater yield. While soil and leaf tissue testing are important to help manage fertilizer programs, the lack of a consistent relationship between soil and plant nutrient status and yield was a reflection of the complicated interactions that occurred among nutrients in these organic production systems. Soil nutrient imbalances and changes in leaf nutrient concentrations associated with extended use of compost + sawdust mulch and fish solubles may lead to growth and yield problems in longer-lived plantings. In addition, the loss of organic matter under weed mat would need to be addressed in long-term plantings for sustainable production.

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The northwestern United States is the largest growing region for blueberries (*Vaccinium corymbosum* L.) in the country and, in 2018, accounted for 48% of the total production (North American Blueberry Council, unpublished data). This region also accounts for more than 60% of the total U.S. organic production of blueberries, which continues to increase due to strong markets and an ideal climate for high yield and quality (DeVetter et al., 2015; Fernandez-Salvador et al., 2017; Strik, 2014, 2016). However, ≈15 years ago, organic production only accounted for ≈2%

of the total blueberry area in the region (Strik, 2016). Most growers at that time were growing the plants on flat ground, mulched with sawdust, and they were fertilizing with fish solubles (Strik, 2016). Many were concerned with their weed management and fertilizer options, and they wondered whether alternative mulches such as weed mat were better than sawdust. Therefore, we initiated a long-term trial to address key questions related to certified organic production of blueberry (Strik et al., 2017a). Results from this trial revealed that the most economical weed

control was achieved with weed mat mulch (Julian et al., 2011, 2012; Strik and Vance, 2017), improved root growth and yield occurred when planting on raised beds (Larco et al., 2013a), higher yield occurred with weed mat than with sawdust mulch, improved yield occurred with lower rates of fertilizer N than those often used commercially, and reduced yield occurred when fertilizing with a fish soluble source, particularly at a high rate (Strik et al., 2017a). Since then, establishing new plantings on raised beds with weed mat mulch has become commonplace, and growers have reduced the total N applied, in general, and avoid using only fish solubles to provide N, supplementing with other sources (Fernandez-Salvador et al., 2017; Strik, 2016).

Weed mat (permeable, woven, polyethylene groundcover) is an inert mulch (Granatstein and Mullinix, 2008) and is allowed for use as a weed barrier by the USDA Organic National Program (USDA-AMS-NOP, 2011). Weed mat is cost-effective for controlling weeds in blueberry (Julian et al., 2012; Magee and Spiers, 1995; Sciarappa et al., 2008; Strik and Vance, 2017) and results in similar or higher yields than sawdust or bark mulches (Larco et al., 2013a; Krewer et al., 2009; Strik et al., 2017a, 2017b). However, soil temperature is higher under weed mat (Larco, 2010; Neilsen et al., 2003b; Strik et al., 2017a; Williamson et al., 2006), which may affect soil properties and nutrient availability.

Growers are inclined to use plant or animal-based composts in organic production systems. Compost can release 3% to 10% of total N for several years after the initial application (Gale et al., 2006; Sikora and Szmidt, 2001). Improved growth and nutrient content of young blueberry plants occurred when compost was used as part of a fertilizer or mulching program (Burkhard et al., 2009; Larco et al., 2013a, 2013b). However, many composts have high pH and high levels of K, as well as many other nutrients (Sullivan et al., 2014). Although a preplant amendment of compost containing lime reduced yield in blueberry (Strik et al., 2017b), composts show promise when used as part of a mulching program (Costello et al., 2019; Strik et al., 2017a), and their impact on soil and plant nutrients in long-term plantings remains a key question among growers.

Highbush blueberry needs to be fertilized at a rate of ≈ 25 – $100 \text{ kg-ha}^{-1} \text{ N}$ per year for optimum growth and production (Bañados et al., 2012; Chandler and Mason, 1942; Eck, 1988; Griggs and Rollins, 1947; Hanson, 2006; Hart et al., 2006). Sullivan et al. (2019) reported equivalent N mineralization rates (58% to 64% of total N converted to mineral N within 28 d) for a variety of fish and feather meal fertilizers commonly used by organic growers. We found that cumulative yield was 3% higher when fertilizing with lower rates of fertilizer N, and that a high rate of fish solubles reduced yield by 35% in ‘Duke’ (Strik et al., 2017a). Fish solubles also reduced root lifespan, particu-

larly under weed mat mulch in this trial (Bryla et al., 2017). The impacts of long-term use of these organic fertilizers on soil and plant nutrients has not been reported in blueberry.

The objectives of this research trial were to evaluate the impact of planting method, cultivar, mulch type, and fertilizer source and rate on plant growth, yield, and fruit quality from the first growing season (2007) through maturity (2016) in northern highbush blueberry (Strik et al., 2017a). In addition, our goal was to assess the impact of these production systems on plant and soil nutrient status and to describe any relationships between soil nutrient level and yield, soil and leaf nutrient status, and leaf and fruit nutrient concentrations. These latter objectives are reported here. The impacts of treatments on plant growth, yield, fruit quality, and costs of production are reported elsewhere (Julian et al., 2012; Larco et al., 2013a, 2013b, 2014; Strik, 2016; Strik and Vance, 2017; Strik et al., 2017a).

Materials and Methods

The 0.4-ha trial was established in Oct. 2006 at Oregon State University’s North Willamette Research and Extension Center (NWREC; Aurora, OR; lat. $45^{\circ}16'47''\text{N}$, long. $122^{\circ}45'23''\text{W}$). Weather data for this site are available from an AgriMet weather station (U.S. Dept. of Interior, 2014). The planting was certified organic starting in the first cropping year (2008) by a USDA-accredited agency (Oregon Tilth, Certified Organic, Corvallis, OR). The soil, which is mapped as a Willamette silt loam (a fine-silty, mixed, superactive mesic Pacific Ultic Argixeroll), contained 3.7% organic matter content at planting. A pooled soil sample taken before planting indicated that soil pH (4.9), organic matter (3.7%), and all nutrients except for Ca (lower than recommended; 536 mg-kg^{-1}) were at appropriate levels for blueberry (Hart et al., 2006; Strik et al., 2017b). No fertilizers or amendments were applied to the field before establishing the treatments. Further details regarding the establishment of the planting are provided elsewhere (Larco et al., 2013a, 2013b). Plant spacing was $0.8 \text{ m} \times 3.0 \text{ m}$ (4385 plants/ha). A permanent grass cover crop was grown in the row aisles and mowed during the growing season, as required. Planting management, disease and pest management, fruit harvest, and pruning were conducted similarly among plots, as described by Strik et al. (2017a, 2007b).

Plants were irrigated using a single line of polyethylene drip tubing (Netafim, Fresno, CA) with 2 L-h^{-1} pressure-compensating, inline emitters every 0.3 m. Irrigation was applied three to seven times per week, as needed, and adjusted to maintain similar levels of soil moisture in each treatment (Strik et al., 2017a).

Treatments. There were 48 treatment combinations arranged in a balanced factorial ($2 \times 4 \times 2 \times 3$) split-split-plot design with five replicates. The main plots were planting

method [raised beds ($\approx 0.3\text{-m}$ high) or flat ground], the subplots were fertilizer rate and source (2 rates $\times$ 2 sources), and the sub-subplots were mulch treatment (“compost + sawdust,” sawdust, or weed mat) and cultivar (early-season ‘Duke’ and midseason ‘Liberty’). Sub-subplots were 4.6-m long with six plants in each sub-sub-plot at establishment.

Mulch treatments were: a) a 9-cm-deep layer of douglas fir sawdust [*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*; $360 \text{ m}^3\text{-ha}^{-1}$]; b) a 4-cm-deep layer of municipal yard-debris compost ($152 \text{ m}^3\text{-ha}^{-1}$) covered by 5-cm-deep douglas fir sawdust ($200 \text{ m}^3\text{-ha}^{-1}$) (compost + sawdust); and c) weed mat [black, woven polyethylene groundcover (water flow rate of 6.8 L-m^{-2} per h; 0.11 kg-m^{-2} ; TenCate Protective Fabrics; OBC Northwest Inc., Canby, OR)]. Holes (20-cm diameter) cut in the weed mat for the plants were mulched with 5-cm-deep douglas fir sawdust ($1.4 \text{ m}^3\text{-ha}^{-1}$). Samples of each batch of compost and sawdust were submitted to Soil Control Laboratory (Watsonville, CA) for analysis of macro- and micronutrient concentration and bulk density. Yard-debris compost was supplied by Rexius Inc. (Eugene, OR). It was prepared from a mixture of woody tree and shrub trimmings collected from urban yard maintenance. Composting took place outdoors in windrows, with $\approx 30 \text{ d}$ of active ($>50^{\circ}\text{C}$) composting, followed by 90 to 180 d of curing at lower temperatures. On a dry weight basis, compost contained the following (g-kg^{-1}): organic matter (499), ash (501), organic C (260), total N (11), total P (2), total K (6), total Ca (9), and total Mg (3). On a dry weight basis, sawdust contained the following (g-kg^{-1}): organic matter (990), ash (10), organic C (491), total N (1), total P (0.2), total K (1), total Ca (2), and total Mg (<0.5). The C:N ratio was 24 for compost and 494 for sawdust. Dry bulk density was 368 g-kg^{-1} for compost and 121 g-kg^{-1} for sawdust. Electrical conductivity (EC) (1:5 w/v) was 1.4 and 0.3 dS-m^{-1} and pH (1:5 w/v) was 7.4 and 4.5 for compost and sawdust, respectively. On a dry weight basis, compost contained $12 \text{ mg-kg}^{-1} \text{ NH}_4\text{-N}$ and $41 \text{ mg-kg}^{-1} \text{ NO}_3\text{-N}$, and sawdust contained $15 \text{ mg-kg}^{-1} \text{ NH}_4\text{-N}$ and $2 \text{ mg-kg}^{-1} \text{ NO}_3\text{-N}$. The organic mulches were initially applied in 2006, just after planting, and were replenished in Jan. 2011, Jan. 2013, and Feb. 2015; in 2015, additional mulch was only needed on raised beds. Table 1 shows the amount of each nutrient supplied through the application of these organic mulches.

Fertilizer source and rate treatments were granular feather meal (11% to 13% N, depending on product or batch) or fish solubles (pH-stabilized; 4% to 5% N). Both were applied at either a “low” or “high” target rate of 28 and $56 \text{ kg-ha}^{-1} \text{ N}$, respectively, in 2007–09 and then increased incrementally as the planting matured to 73 and $140 \text{ kg-ha}^{-1} \text{ N}$, respectively, by 2013. Samples of each fertilizer were submitted to Brookside Laboratories (New Bremen, OH) for analysis of

nutrient concentration with rates of nutrients applied from fertilizer calculated and presented in Table 2. In some instances, the actual application rate of N was different from the target rate because the nutrient analysis did not match the percent of N as stated on the product label. Feather meal was applied in two equal split-applications in March and May. In weed mat plots, the feather meal was concentrated in the openings in 2007–10, and later, once the zippered weed mat was installed (Strik et al., 2017a), it was broadcast on the entire plot in-row area underneath the weed mat. Fish solubles fertilizer was diluted with 10 parts water (v/v) and applied by hand as a drench around the base of the plants in 2007–09, side-dressed with a sprayer on each side of the row in 2010, and injected through the drip system (fertigation) in 2011–16. Fertilization with fish solubles was split into seven equal applications every 2 weeks from mid April to early July.

Leaf tissue analyses indicated that the concentration of B was low (<30 ppm) in 2009 and 2012–15 (Hart et al., 2006). Therefore, mineral borate was applied to the soil in

Autumn 2010, Spring 2013, and Spring 2014, and boric acid was applied to the foliage in Spring 2010, 2015, and 2016 at rates of 0.7–2.2 kg·ha⁻¹ B per year (Table 2). The concentration of Ca and Mg were also low in the leaves in 2012. Therefore, gypsum and epsom salt were applied at rates of 245 kg·ha⁻¹ Ca and 56 kg·ha⁻¹ Mg, respectively, before the 2013 growing season (Table 2).

The cultivars were chosen because of their popularity at the time and their different fruiting seasons. Fertility management was also expected to be more difficult in ‘Duke’ (more sensitive to N rate and soil pH) than in ‘Liberty’, based on our experience in conventional systems.

Data collection. Plant tissue (most recent fully expanded leaves in late July to early August from three replicates) samples were collected each year. Leaves were not washed before submission, as recommended by Hart et al. (2006). Ripe fruit were sub-sampled from the second harvest of both cultivars in 2015 and 2016; the only plants that were sampled in this case were those grown on raised beds mulched with sawdust or weed mat and fertilized with feather meal or fish

solubles [represented the largest treatment differences for yield (Strik et al., 2017a)]. Tissue samples were analyzed for macro- and micronutrients (plus carbon and moisture content for fruit) by Brookside Laboratories.

Soil samples were collected in autumn of each year (five replicates per treatment). Duke was the only cultivar sampled (to reduce costs and because fewer differences were expected between cultivars for soil than for leaf tissue testing). Two samples were taken per plot and pooled, one per side of each drip line (east and west side of the row) between two plants. Sampling depth was 0.2 m using a 2.4-cm diameter chrome-plated steel soil probe (Soil Sampler Model Hoffer, JBK Manufacturing, Dayton, OH). Mulch was removed from the soil surface before taking the samples and replaced afterward. Soil samples were air dried and sent for analysis to Brookside Laboratories. Extractable soil K, Ca, Mg, Na, B, Cu, Mn, Zn, and Al were determined by ICP after extraction of the nutrients using the Mehlich 3 method (Mehlich, 1984). Soil P was extracted with the Bray-1 method and then determined by ICP. Soil NO₃-N and NH₄-N

Table 1. Total nutrients applied as part of the sawdust and yard-debris compost topped with sawdust mulching treatments in a certified organic production systems trial of northern highbush blueberry at Oregon State University’s North Willamette Research and Extension Center, 2006–16.

Yr	Mulch	Macronutrients (kg·ha ⁻¹)					Micronutrients (kg·ha ⁻¹)			
		N	P	K	Ca	Mg	B	Mn	Cu	Zn
2006	Sawdust	51	12	2	92	14	0.1	2.8	0.2	0.5
	Compost	616	132	31	952	302	0.4	30.2	4.2	10.2
2011	Sawdust	37	3	40	53	7	0.8	4.5	0.2	0.4
	Compost	615	101	364	727	179	1.2	35.2	2.1	8.4
2013	Sawdust	69	5	22	30	6	2.2	1.4	0.1	0.3
	Compost	613	97	342	613	143	2.0	27.1	1.9	6.6
2015 ²	Sawdust	104	8	24	42	6	0.2	1.5	0.3	0.5
	Compost	430	70	224	482	114	0.83	21.0	2.72	5.7

²Sawdust and compost mulch were only applied to raised beds in 2015, because sufficient quantities were still present on flat ground treatments.

Table 2. Total nutrients from organic fertilizers applied at low and high rates in a certified organic production systems trial of northern highbush blueberry at Oregon State University’s North Willamette Research and Extension Center, 2007–16. Target treatment rates are based on the amount of N listed on the label of the fertilizer. Actual rates applied are based on fertilizer nutrient content analysis (Brookside Laboratory, New Bremen, OH).

Fertilizer type ^z	Rate	Target N rate per yr (kg·ha ⁻¹)	Macronutrients (kg·ha ⁻¹)						Micronutrients (g·ha ⁻¹) ^z				
			N ^y	P	K	Ca	Mg	Na	B	Fe	Mn	Cu	Zn
2007–09													
Feather meal	Low	28	87	12	1.2	18	1.8	NA ^x	21	NA	30	6	81
	High	56	171	24	2.4	36	3.6	NA	42	NA	60	12	162
Fish solubles	Low	28	87	33	123	1.5	1.2	NA	3	NA	6	360	78
	High	56	171	66	246	3	2.4	NA	6	NA	12	720	156
2010–12													
Feather meal	Low	50	140	5	4	15	1	2	23	1738	185	57	736
	High	101	278	11	8	31	3	4	46	3447	367	113	1460
Fish solubles	Low	50	146	19	123	12	2	47	120	5152	187	382	512
	High	101	292	38	247	23	5	94	240	10313	375	766	1025
2013–16													
Feather meal	Low	73	264	7	9	22	2	5	16	2978	343	97	1420
	High	140	530	14	18	44	3	10	31	6028	699	193	2846
Fish solubles	Low	73	278	55	103	3	14	115	337	2963	304	65	1345
	High	140	537	107	198	6	27	223	650	5715	590	125	2605
2007–16													
Additional fertilizer			247		56		8800						

²Products used varied by year. Feather meal products applied: Nature Safe (Irving, TX; 2007–09); Pro-Pell-It (St. Paul, OR; 2010); Bridgwell Agriculture Par 4 (Clackamas, OR; 2011); California Organic Fertilizers, Phyta Grow Super N (Fresno, CA; 2012–15); Pacific Calcium 11–0–0 (Tonasket, WA; 2016). Fish solubles applied: Fish Agra (Edmonton, Alberta, Canada; 2007–10); TRUE Organic Products TRUE 402 (Spreckels, CA; 2011–12); TRUE Organic Products TRUE 512 (Spreckels, CA; 2013–15); California Organic Fertilizers, Phytamin 420 (Fresno, CA; 2015–16). Additional fertilizers applied: 20 Mule Team Solubor (Chicago, IL; 2010, 2013–16); Pro-Pell-It Gypsum (St. Paul, OR; 2013); Marion Ag Service Magnesium Sulfate (St. Paul, OR; 2013).

³Values shown are cumulative over the indicated time period.

⁴NA = not available.

were determined using automated colorimetric methods after extraction with 1 M KCl (Dahnke, 1990). Soil organic matter and pH were measured using Loss-On-Ignition at 360 °C (Nelson and Sommers, 1996) and the 1:1 soil:water method (McLean, 1982), respectively. Levels of SO₄-S were not included because these are not generally tested in less arid regions (Horneck et al., 2011).

Statistical analysis. Data were analyzed using PROC MIXED in SAS software package version 9.3 (SAS Institute, Cary, NC). Leaf and soil nutrients were first characterized across years using a split-split-split plot design [year as the main effect (n = 10 for leaves and n = 9 for soil), planting method as the sub-plot (n = 2), fertilizer rate and source as the sub-sub-plot (n = 4), and combinations of cultivar and mulch as sub-sub-subplots (n = 6)] and then re-analyzed within years using a complete factorial of the original split-split plot design. Contrasts were used to compare the effects of fertilizer source and rate and mulch type on measured variables. Means were separated at the 5% level using Tukey's honestly significant difference test. Correlation analysis was performed using PROC CORR to determine relationships between leaf nutrients in a particular year and yield of that same year or in the following year within individual plots of 'Duke' and 'Liberty' (n = 240). Average fruit nutrient concentration for the season (Fernandez-Salvador, unpublished data) was correlated with leaf nutrient concentration in the same year for plots considered individually for both cultivars in 2015–16 (n = 80). 'Duke' was also analyzed for correlations between soil nutrient concentrations and yield, as well as between soil and leaf and soil and fruit nutrient concentrations (n = 120). Yield data are presented in our previous work (Strik et al., 2017a) with any nutrient relationships presented and described herein.

Results

There was a significant effect of year and many interactions between production sys-

tems and year for soil pH, organic matter, and nutrient levels (Table 3). Because soil testing can be quite variable from year to year (due to sampling method and weather, particularly rain), we are focusing on the more significant effects of production system treatments on various soil nutrient levels or properties and will mention the more notable effects over the study period.

Soil pH and organic matter

Soil pH. Soil pH remained between 4.5 and 5.5 in each treatment during the study (data not shown). However, when averaged across the fertilizer sources, soil pH was lower in plots fertilized with a high N rate than a lower N rate in 2008 (5.1 vs. 5.3, respectively) and 2011–16 (5.1 vs. 5.3, respectively). From 2012 to 2016, soil pH was highest under weed mat (5.3), intermediate with compost + sawdust (5.2) and lowest under sawdust (5.0). During this same period, soil pH was higher on raised beds (5.3) than on flat ground (5.1). There was a significant interaction between mulch type and fertilizer treatment on soil pH because soil pH was highest under weed mat when the plants were fertilized with the low rate of fish solubles and highest under compost + sawdust when the plants were fertilized with the high rate of either fertilizer source (data not shown).

Soil organic matter. Soil organic matter responded to mulch treatment. Over the final 5 years of the study (2012–16), soil organic matter content averaged 4.1% under compost + sawdust, 3.3% under sawdust, and 2.9% under weed mat.

Soil nutrients

Soil N. Soil NO₃-N was significantly higher in raised beds (11 ppm) than flat ground (7 ppm) when the plants were fertilized with the high rate of fish solubles and lowest when the plants were fertilized with the low rate of feather meal (3 ppm). In general, soil NO₃-N levels were higher on raised beds than on flat ground, regardless of mulch (data not shown). Averaged over planting method, soil NO₃-N was lower under sawdust and compost + sawdust mulch

than under weed mat (Fig. 1). With sawdust and compost + sawdust mulch, soil NO₃-N was higher in most years when the plants were fertilized with the high rate of fish solubles. In contrast, with weed mat mulch, the high rate of fish increased soil NO₃-N in the early years of the study, whereas levels were highest for the high rate of feather meal in the later years (Fig. 1C). Soil NH₄-N was relatively low when the plants were mulched with sawdust or compost + sawdust (2–8 ppm), regardless of fertilizer source or rate, whereas with weed mat mulch, levels were as high as 20–25 ppm when the plants were fertilized with fish.

Soil P. On average, soil P was higher when the plants were fertilized with the high rate of either fertilizer source (241 ppm) than with the low rate of either source (224 ppm). Soil P was also higher, on average, under compost + sawdust (240 ppm), intermediate with weed mat (233 ppm), and lowest with sawdust mulch (224 ppm); however, all treatments were well above the recommended sufficiency level for soil P in northern highbush blueberry (Hart et al., 2006).

Soil cations. Soil K was higher when the plants were fertilized with the high rate of either fertilizer source in 2008 and 2011, but thereafter, there was either no effect of treatment or fertilization with fish solubles increased soil K relative to feather meal from 2012 to 2016 (Fig. 2A). On average, soil K was higher when the plants were mulched with compost + sawdust (357 ppm) than with sawdust or weed mat (219 ppm), particularly on flat ground (data not shown). Soil K was excessive (compost + sawdust mulch) or above the recommended soil sufficiency range by the end of the study (Hart et al., 2006).

Soil Ca was higher when the plants were fertilized with feather meal than with any other fertilizer treatment in 2008 and lower when they were fertilized with the high rate of fish solubles in 2011–14 (Fig. 2B). By the end of the study period, soil Ca was highest when the plants were grown with the low rate of either fertilizer source. Soil Ca was highest under compost + sawdust mulch and lowest

Table 3. Results of analysis of variance for the impact of year (2008–16; n = 9), planting method (raised bed or flat ground; n = 2), fertilizer source and rate (feather meal or fish solubles at low or high N rates; n = 4), and mulch (sawdust, yard-debris compost topped with sawdust, weed mat; n = 3) on soil pH and level of organic matter and nutrients in 'Duke'.

Factor ²	Soil organic		Soil nutrient concn (ppm)											
	Soil pH	matter (%)	NO ₃	NH ₄	P	K	Ca	Mg	B	Fe	Mn	Cu	Zn	Al
Year (yr)	<0.0001	<0.0001	0.0009	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Planting method (PM)	<0.0001	<0.0001	NS	NS	NS	0.0009	NS	<0.0001	0.0206	0.0173	NS	NS	<0.0001	NS
Yr × PM	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.002	NS	NS
Fertilizer (Fert)	<0.0001	0.0011	<0.0001	0.0404	0.0001	<0.0001	<0.0001	<0.0001	NS	0.0017	<0.0001	NS	NS	<0.0001
Yr × Fert	<0.0001	NS	<0.0001	<0.0001	NS	<0.0001	0.0007	0.0034	NS	NS	<0.0001	0.0002	NS	0.0035
PM × Fert	0.0154	NS	0.0002	NS	NS	NS	0.0001	0.002	NS	0.0008	NS	NS	NS	0.0026
Yr × PM × Fert	NS	NS	NS	NS	NS	NS	NS	NS	0.0212	NS	NS	0.0212	NS	0.0016
Mulch	<0.0001	<0.0001	<0.0001	<0.0001	0.0051	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	<0.0001	<0.0001
Yr × Mulch	<0.0001	<0.0001	<0.0001	<0.0001	NS	<0.0001	<0.0001	<0.0001	0.0252	NS	0.0021	NS	<0.0001	0.0001
PM × Mulch	NS	<0.0001	0.0146	NS	NS	<0.0001	NS	0.0149	NS	NS	0.01	NS	<0.0001	<0.0001
Yr × PM × Mulch	0.0014	NS	0.0291	NS	NS	0.044	NS	0.0057	NS	NS	NS	NS	NS	NS
Fert × Mulch	<0.0001	NS	0.0067	0.0408	NS	0.0057	0.0067	0.0002	NS	NS	<0.0001	NS	0.0166	0.0245
Yr × Fert × Mulch	NS	NS	<0.0001	<0.0001	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
PM × Fert × Mulch	NS	NS	NS	NS	NS	0.0009	NS	NS	NS	NS	<0.0001	NS	NS	NS

²Results from full analysis of variance. Nonsignificant (NS) or actual P value provided when significant (P < 0.05).

with sawdust for several years during the study period, with soil levels of 1110 and 760 ppm, respectively, at the end of the study.

Soil Mg was higher when the plants were fertilized with the low rate of fish solubles from 2012 to 2016 and lower with the high rate of feather meal than the other treatments in 2016 (Fig. 2C). Soil Mg was also higher on raised bed plantings (158 ppm) than on flat ground (136 ppm). Weed mat (173 ppm) and compost + sawdust (153 ppm) mulch led to increased soil Mg compared with sawdust (115 ppm), regardless of fertilizer treatment.

Soil micronutrients. Although there were treatment effects on the level of many soil micronutrients (Table 3), the focus of this study was on soil B because of the measured plant responses and no other micronutrient was considered deficient (Hart et al., 2006; Horneck et al., 2011). Soil Fe, Cu, Mn, Zn, and Al ranged from 302 to 339 ppm, 0.7 to 1.4 ppm, 14 to 23 ppm, 1.1 to 3.9 ppm, and 1233 to 1483 ppm, respectively, over the last 5 years of the study (2012–16; data not shown).

Fertilization with the high rate of feather meal increased soil B (0.53 ppm) relative to the other treatments (averaged 0.42 ppm) in 2016, but only in the raised bed plantings. There was no effect of mulch on soil B during the study period, other than in 2015–16, when levels were higher under compost + sawdust (0.44–0.53 ppm) than under the other mulches (averaged 0.38–0.42 ppm). Soil B was at (compost + sawdust) or just below the recommended soil sufficiency level in each treatment (Hart et al., 2006).

Leaf nutrients

The impacts of year, planting method, fertilizer, mulch, and cultivar on leaf nutrient concentration over this 10-year study were complex, with many interactions among the treatments (Table 4). Although there was a main effect of year on the concentration of all leaf nutrients, in all cases, there was an interaction of year with at least one production system treatment (planting method, fertilizer, mulch, or cultivar). Thus, changes in leaf nutrients over the study period (years) are described, with production system interaction effects presented when relevant.

Leaf N. There was a year $\times$ fertilizer $\times$ cultivar interaction on the concentration of leaf N (Table 4). In general, leaf N concentration was higher in young plants than in mature plants in both cultivars (Figs. 3A and 4A). Plants fertilized with fish solubles had higher leaf N than those fertilized with feather meal, and a greater rate of N application led to higher leaf N for most years in both cultivars. In ‘Liberty’, there were relatively large differences in leaf N among the fertilizer treatments in all years of the study, whereas in ‘Duke’, differences between fertilizers were relatively small from 2010 to 2013.

Fertilization with fish solubles, particularly at the high rate, increased leaf N concentration in all mulch treatments from 2007 to 2009 and in sawdust and compost + sawdust mulch in most of the other years

Fig. 1. Effect of fertilizing with low (29–73 kg·ha⁻¹ N per year) or high (57–140 kg·ha⁻¹ N per year) rates of feather meal or fish solubles on soil nitrate-N (NO₃-N) in ‘Duke’ northern highbush blueberry plants grown in a certified organic planting at Oregon State University’s North Willamette Research and Extension Center from the second through the tenth growing season (2008–16) as affected by mulch: (A) sawdust, (B) compost topped with sawdust (compost + sawdust), and (C) weed mat. Means are averaged over planting method (flat ground and raised beds) treatment. Error bars represent ± 1 SE.

(Fig. 5A–C). With weed mat mulch, there were fewer effects of fertilizer treatment on leaf N from 2010 to 2016. On average, leaf N was highest when the plants were fertilized with the high rate of fish (1.79%) and lowest

when they were fertilized with the low rate of feather meal (1.56%). Plants mulched with weed mat had a higher leaf N concentration than those mulched with sawdust, regardless of the source or rate of fertilizer applied in

Fig. 2. Effect of fertilizing with low (29–73 kg·ha⁻¹ N per year) or high (57–140 kg·ha⁻¹ N per year) rates of feather meal or fish solubles in ‘Duke’ northern highbush blueberry plants grown in a certified organic planting at Oregon State University’s North Willamette Research and Extension Center from the second through the tenth growing season (2008–16) on soil (A) K, (B) Ca, and (C) Mg. Means are averaged over planting method (raised beds and flat ground) and mulch (sawdust, compost + sawdust, and weed mat) treatments. Error bars represent ± 1 SE.

‘Duke’ (Fig. 6A) and for all fertilizers except the high rate of fish solubles in ‘Liberty’ (Fig. 6B). In addition, plants mulched with compost + sawdust had higher leaf N than those mulched with sawdust when ‘Duke’ was

fertilized with the low rate of fish solubles, but there were few differences in leaf N among the mulch treatments in ‘Liberty’.

In general, leaf N concentration was highest when the plants were grown on raised

beds with weed mat mulch, but only in the later years of the study (2013–16) (data not shown). On average, over the study period and treatments, ‘Duke’ had higher leaf N and S than ‘Liberty’ (1.68% and 1.65% N and 0.12% vs. 0.11% S, respectively).

Leaf N concentration. Leaf N concentration was below the recommended sufficiency range (1.76% to 2.0%; Hart et al., 2006) in most treatments from 2012 to 2016.

Leaf S. The impact of year and fertilizer treatment on leaf S concentration was similar to leaf N (Figs. 3F and 4F). Plants grown on raised beds had a higher leaf S than those on flat ground, regardless of mulch type. However, the largest differences were found with weed mat (0.119% vs. 0.115%) and sawdust mulch (0.116% vs. 0.113%), compared with relatively little difference with compost + sawdust mulch (0.115% vs. 0.114%), for raised and flat plantings, respectively.

Leaf P. There was a year $\times$ fertilizer $\times$ cultivar interaction on leaf P (Table 4), with concentrations tending to decline from planting establishment to maturity in both cultivars (Figs. 3B and 4B). Fertilization with the high rate of fish increased leaf P relative to the low rate of feather from 2008 to 2016, with larger differences when the plants were young.

There was also a significant interaction among year, planting method, and mulch on leaf P concentration (Table 4). Leaf P was higher, in general, for plants grown with weed mat on raised beds, but only in the later years of the study (2013–16) (data not shown). On average, leaf P was higher in plants grown on raised beds (0.12%) than on flat ground (0.11%), especially when they were fertilized with the high rate of feather meal (0.12% vs. 0.11%, respectively) or the low rate of fish solubles (0.12% vs. 0.11%, respectively).

Leaf P was higher in plants mulched with weed mat than with sawdust, but differences were greater in ‘Duke’ than in ‘Liberty’ (Fig. 6C and D). In ‘Duke’, leaf P was greater with compost + sawdust than with sawdust when the plants were fertilized with fish solubles; however, there was little effect of these mulches on leaf P in ‘Liberty’. On average, over the study period and treatments, ‘Duke’ had higher leaf P (0.14%) than ‘Liberty’ (0.11%). Leaf P was low (0.11% to 0.14%) in many treatments in 2009 and 2012–16, relative to published sufficiency levels (0.11% to 0.40%) (Hart et al., 2006).

Leaf cations. There was a year $\times$ fertilizer $\times$ cultivar interaction on the concentration of leaf K, Mg, and Ca (Table 4). Plants fertilized with fish solubles, particularly at the high rate in many years, had greater leaf K in both cultivars (Figs. 3C and 4C). There was less of an impact of rate of feather meal application on leaf K than with fish. Leaf Ca concentration increased, in general, from planting establishment to maturity in both cultivars (Figs. 3D and 4D). In ‘Duke’, leaf Ca was highest when the plants were fertilized with feather meal, particularly at the high rate in most years of the study (Fig. 3D), whereas in ‘Liberty’, this treatment was only greater

Table 4. Results of analysis of variance for the impact of year (2007–16; n = 10), planting method (raised bed or flat ground; n = 2), fertilizer source and rate (feather meal or fish solubles at low or high N rates; n = 4), mulch (sawdust, yard-debris compost topped with sawdust, weed mat; n = 3) and cultivar (Duke, Liberty; n = 2) on leaf nutrient concentration (collected in late July–early August of each year).

Factor ²	Leaf macronutrient concn (%)						Leaf micronutrient concn (ppm)					
	N	P	K	Ca	Mg	S	B	Fe	Mn	Cu	Zn	Al
Year (yr)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0003	<0.0001	<0.0001	<0.0001	<0.0001	0.0338	<0.0001
Planting method (PM)	0.0048	<0.0001	<0.0001	<0.0001	0.0057	0.0019	<0.0001	0.0259	NS ²	NS	NS	0.0109
Yr × PM	NS	0.0416	NS	NS	NS	NS	0.0094	NS	NS	NS	NS	NS
Fertilizer (Fert)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	NS	<0.0001	0.0007	NS	NS
Yr × Fert	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	NS	<0.0001	0.0247	NS	NS
PM × Fert	NS	0.0186	NS	<0.0001	0.0002	NS	0.0007	NS	0.0119	NS	NS	NS
Yr × PM × Fert	NS	NS	NS	0.0387	NS	NS	NS	NS	NS	NS	NS	NS
Mulch	<0.0001	<0.0001	<0.0001	<0.0001	0.0003	<0.0001	<0.0001	NS	<0.0001	NS	NS	0.0002
Yr × Mulch	<0.0001	<0.0001	<0.0001	0.0056	<0.0001	<0.0001	<0.0001	NS	0.0087	NS	NS	NS
PM × Mulch	NS	0.0488	0.0001	NS	NS	0.0018	0.0317	NS	NS	NS	NS	NS
Yr × PM × Mulch	0.0002	<0.0001	0.0138	NS	0.005	NS	0.0021	NS	<0.0001	NS	NS	NS
Fert × Mulch	0.0471	NS	NS	<0.0001	0.0257	NS	<0.0001	NS	NS	NS	NS	NS
Yr × Fert × Mulch	0.0004	NS	0.0001	0.0151	0.0001	0.0385	NS	0.0165	NS	0.0043	NS	NS
PM × Fert × Mulch	NS	NS	NS	0.0408	0.0445	NS	NS	NS	NS	NS	NS	NS
Cultivar (cv.)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0242	<0.0001	<0.0001	<0.0001	0.0124
Yr × cv.	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0024	<0.0001	0.0142
PM × cv.	NS	0.0409	NS	0.0004	NS	NS	NS	0.0291	0.0066	NS	NS	NS
Yr × PM × cv.	NS	<0.0001	NS	NS	0.0247	NS	NS	NS	NS	NS	NS	NS
Fert × cv.	NS	<0.0001	0.0016	<0.0001	<0.0001	NS	0.092	0.0336	<0.0001	NS	NS	NS
Yr × Fert × cv.	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0340	0.0002	NS	<0.0001	NS	NS	NS
PM × Fert × cv.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Mulch × cv.	NS	NS	0.0258	<0.0001	<0.0001	NS	NS	NS	0.0005	NS	NS	NS
Yr × Mulch × cv.	NS	NS	NS	NS	0.0461	NS	NS	NS	0.0003	NS	NS	NS
PM × Mulch × cv.	NS	NS	NS	0.016	NS	NS	NS	NS	NS	NS	NS	NS
Fert × Mulch × cv.	0.0382	0.0005	0.0140	NS	NS	0.0061	NS	NS	0.0007	NS	NS	NS

²Results from full analysis of variance. NS = nonsignificant.

than fish in the first growing season and at maturity (Fig. 4D). In both cultivars, leaf Ca was lowest when the plants were fertilized with the high rate of fish solubles in most years. Leaf Mg increased from 2007 to 2009 but declined in 2010 and 2011 and increased again from 2012 to 2015 (Figs. 3E and 4E). In both cultivars, the leaf Mg was particularly low in 2012. The impact of fertilizer treatment on leaf Mg was greatest during establishment of the planting, with the lowest levels in fish-fertilized plants.

Fertilization with fish solubles, particularly at the high rate, increased leaf K concentration in all mulch treatments from 2007 to 2009 and in most of the other years of the study for the sawdust and compost + sawdust mulches (Fig. 5D–F). There were fewer effects of fertilizer treatment on leaf K from 2010 to 2016 with weed mat mulch. In general, leaf K was lowest when fertilizing with the low rate of feather meal.

Although there was little effect of fertilizer rate on leaf Ca when the plants were mulched with compost + sawdust, fertilizing with the high rate of fish reduced leaf Ca in plants mulched with sawdust or weed mat (Fig. 5G–I). In contrast, fertilizing with the low rate of feather meal increased leaf Ca from 2011 to 2016 in plants mulched with the sawdust.

Leaf Mg concentration increased from 2007 to 2009 when the plants were fertilized with fish solubles in each mulch treatment and when they were fertilized with feather meal and mulched with sawdust or compost + sawdust (Fig. 5J–L). Leaf Mg was lower when the plants were fertilized with fish solubles than with feather meal, but generally only when plants were in their first growing season.

There was a significant interaction of year, planting method, and mulch on leaf K and Mg concentration (Table 4). Leaf K was higher, in general, for plants grown with weed mat on raised beds, but only in the later years of the study (2013–16) (data not shown). Plants grown with sawdust mulch had lower leaf K than those grown with other mulches in 2007–08 and 2013–16, but only on flat ground (data not shown). Weed mat increased leaf K compared with sawdust mulch in both cultivars, regardless of fertilizer treatment (Fig. 6E and F). In addition, compost + sawdust mulch increased leaf K compared with using sawdust alone for all fertilizers in ‘Duke’ and all but the high rate of fish solubles in ‘Liberty’.

There was little effect of planting method on leaf Mg, except for when the plants were young and had higher levels of leaf Mg on flat ground than on raised beds (data not shown). ‘Duke’ had higher leaf Mg than ‘Liberty’ for 7 of the 10 years of the study, averaging 0.17% and 0.15%, respectively.

Plants grown on raised beds had higher leaf Ca when fertilized with feather meal than with fish solubles throughout the entire study period, regardless of the rate of fertilizer applied (Fig. 7A). Although leaf Ca tended to be higher on flat ground for plants fertilized with feather meal than with fish solubles, leaf Ca was similarly high for plants fertilized with the low rate of fish on raised beds during many years of the study (Fig. 7B). Plants grown on raised beds had higher leaf Ca with sawdust mulch than weed mat when they were fertilized with either rate of feather meal (Fig. 8A), but on flat ground, this only occurred at the low rate of feather meal (Fig. 8B). Leaf Ca was lower with compost +

sawdust than with sawdust mulch at the low rate of either fertilizer source on raised beds, but only with the low rate of feather meal on flat ground.

In ‘Duke’, leaf Ca was higher, regardless of mulch type, when the plants were grown on flat ground (0.54%) than on raised beds (0.50%), whereas in ‘Liberty’, plants mulched with compost + sawdust or weed mat had higher leaf Ca on raised beds (0.51%) than on flat ground (0.49%). In both cultivars, leaf Ca was highest with sawdust mulch (0.53%) and tended to be lowest with weed mat (0.50%).

When mulching with compost + sawdust on raised beds, fertilization with the low rate of fish solubles led to lower leaf Mg than fertilizing with either rate of feather meal (Fig. 8C). On flat ground, lower leaf Mg was often found with weed mat mulch, particularly when the plants were grown with a higher rate of fertilizer (Fig. 8D).

Over the study period, leaf K was higher and leaf Mg and Ca were lower when plants were grown with weed mat when compared with the sawdust or compost + sawdust mulches (Fig. 5D–L). On average, mulching with sawdust, relative to the compost + sawdust, increased leaf Mg, but had no effect on leaf K or Ca (data not shown). Leaf K was highest, on average, when the plants were fertilized with the high rate of fish (0.56%) and lowest when they were fertilized with the low rate of feather meal (0.49%). Leaf Ca and Mg, on the other hand, were highest, on average, when the plants were fertilized with the low rate of feather meal (0.56% and 0.164%, respectively) and lowest when they were fertilized with the high rate of fish (0.47% and 0.157%, respectively). Over the study period and

Fig. 3. Effect of fertilizing with low ($29\text{--}73\text{ kg}\cdot\text{ha}^{-1}$ N per year) or high ($57\text{--}140\text{ kg}\cdot\text{ha}^{-1}$ N per year) rates of feather meal or fish solubles in 'Duke' northern highbush blueberry plants grown in a certified organic planting at Oregon State University's North Willamette Research and Extension Center from the first through the tenth growing season (2007–16) on leaf (A) N, (B) P, (C) K, (D) Ca, (E) Mg, and (F) S concentration. Means are averaged over planting method (raised beds and flat ground) and mulch (sawdust, compost + sawdust, and weed mat) treatments. Error bars represent ± 1 SE.

treatments, 'Duke' had higher leaf K, Ca, and Mg concentrations than 'Liberty', and for both cultivars, plants grown on raised beds had higher leaf K and lower leaf Ca and Mg than those grown on flat ground (data not shown).

Leaf K was below sufficiency (0.41% to 0.70%; Hart et al., 2006) in 'Liberty' in 2014 and above recommended levels in plants fertilized with the high rate of fish in 2008. Leaf Ca was also below recommended levels (0.41% to 0.80%) in 2012 when the plants fertilized with the high rate of fish solubles, whereas leaf Mg was below sufficiency levels (0.13% to 0.25%) that year in most treatments. All three of these nutrients were sufficient in each treatment in other years.

Leaf micronutrients. There was a significant interaction of year, planting method, and

mulch on leaf B concentration (Table 4). Plants grown on flat ground or raised beds had higher leaf B with compost + sawdust mulch when establishing (2007–10), but weed mat led to higher leaf B than the other mulches when the plants were grown on flat ground from 2014 to 2016 (data not shown). Leaf B was also greater when the plants were grown on flat rather than raised beds, particularly when they were fertilized with the low rate of feather meal (35 ppm vs. 28 ppm, respectively). When the plants were mulched with sawdust or compost + sawdust, leaf B was higher with feather meal (averaged 30 ppm) than with fish solubles (26 ppm). In contrast, with weed mat mulch, leaf B was higher with the low rate of feather meal (31 ppm) than with the other fertilizer treatments (averaged 28 ppm). In 'Duke' and 'Liberty', leaf B was higher in plants fertilized with

feather meal (43 ppm and 35 ppm, respectively) than with fish solubles (20 ppm for both cultivars) in 2007 ('Duke') and 2007–08 ('Liberty'), but fertilizer effects on leaf B were relatively small thereafter (data not shown). On average, over the study period and treatments, 'Duke' had higher leaf B concentration than 'Liberty' (data not shown). Leaf B was below sufficiency levels (30–80 ppm; Hart et al., 2006) in most years of the study.

There was a significant interaction of year, planting method, and mulch on leaf Mn concentration (Table 4). In general, mulch had more of an effect on leaf Mn when the plants were grown on flat ground than on raised beds (data not shown). However, 'Liberty' had higher leaf Mn (126 ppm) than 'Duke' (119 ppm), but only when the plants were grown on raised beds; there was

Fig. 4. Effect of fertilizing with low (29–73 kg·ha⁻¹ N per year) or high (57–140 kg·ha⁻¹ N per year) rates of feather meal or fish solubles in ‘Liberty’ northern highbush blueberry plants grown in a certified organic planting at Oregon State University’s North Willamette Research and Extension Center from the first through the tenth growing season (2007–16) on leaf (A) N, (B) P, (C) K, (D) Ca, (E) Mg, and (F) S concentration. Means are averaged over planting method (raised beds and flat ground) and mulch (sawdust, compost + sawdust, and weed mat) treatments. Error bars represent ± 1 SE.

no difference between cultivars on flat ground (120 ppm, on average). Fertilization with the high rate of fish increased leaf Mn relative to the other fertilizer treatments in all but 2015 (‘Liberty’ only) and 2016. Leaf Mn was within published sufficiency levels (Hart et al., 2006) for all treatments in all years of the study.

Leaf Fe and Al concentrations were quite variable throughout the study period, ranging from 56 to 210 ppm and 87 to 226 ppm, respectively, likely due to dust being on sampled leaves that were not washed (Hart et al., 2006; Strik and Vance, 2015). Leaf Cu was much higher in the first growing season (6 ppm) than in subsequent years (1.8–4.6 ppm), and ‘Duke’ had higher leaf Cu (3.4 ppm) than ‘Liberty’ in most years (averaging 2.7 ppm). ‘Duke’ had higher leaf Zn (12.4

ppm) than ‘Liberty’ (8.9 ppm) over the study period. Leaf Zn was within published sufficiency levels (8–30 ppm), whereas leaf Cu was below sufficiency (5–15 ppm; Hart et al., 2006) for most treatments and years of the study.

Relationships among soil and plant nutrients and yield

Correlations between soil pH and leaf nutrients. Soil pH was negatively correlated to leaf Mn concentration in 6 out of the 10 years of the study and to leaf Al concentration in 2015 (data not shown).

Correlations between soil nutrients and nutrients in the plant leaves and fruit. Soil nutrient concentrations were usually uncorrelated with leaf nutrient concentrations in a given year. Exceptions included positive

correlations between leaf N and soil NO₃-N (2008–11, 2014) and NH₄-N (2008, 2010), leaf and soil P (2010, 2012, 2016), leaf and soil K (2008, 2011–13), and leaf and soil B (2015), and a negative correlation between leaf and soil Mg (2014) (data not shown). Fruit K concentration was also positively correlated to available soil K ($r = 0.66$; $P = 0.002$) in ‘Duke’ in 2015; however, there was no correlation between fruit and soil K in 2016 or for any other nutrient in the fruit and soil in either year that fruit were tested (data not shown).

Correlations between nutrients in the leaves and fruit. Leaf K was negatively correlated to leaf Ca from 2008 to 2014 in ‘Duke’ (Fig. 9A) and in 4 years of the study in ‘Liberty’ (Fig. 9B). Leaf K was also negatively correlated to leaf Mg in 4 years of the

Fig. 5. Effect of fertilizing with low (29–73 kg-ha⁻¹ N per year) or high (57–140 kg-ha⁻¹ N per year) rates of feather meal or fish solubles when mulched with sawdust, yard-debris compost topped with sawdust (compost + sawdust) or weed mat for northern highbush blueberry plants grown in a certified organic planting at Oregon State University's North Willamette Research and Extension Center from the first through the tenth growing season (2007–16). Means are averaged over planting method (raised beds and flat ground) and cultivar (Duke and Liberty) treatments. Leaf N concentration for (A) sawdust, (B) compost + sawdust, and (C) weed mat; leaf K concentration for (D) sawdust, (E) compost + sawdust, and (F) weed mat; leaf Ca for (G) sawdust, (H) compost + sawdust, and (I) weed mat; and leaf Mg for (J) sawdust, (K) compost + sawdust, and (L) weed mat. Error bars represent ± 1 SE.

study for both cultivars (data not shown). Leaf Ca was negatively correlated to leaf Mg in 4 years in both cultivars and negatively correlated to leaf N in 'Duke' (6 years) and 'Liberty' (3 years) (data not shown).

Fruit Ca concentration was positively correlated to leaf Ca in 'Duke' in 2015 ($r = 0.66$; $P = 0.02$) and negatively correlated to leaf Ca in 'Liberty' in 2016 ($r = -0.064$; $P = 0.026$). Furthermore, in 'Liberty', fruit S was positively correlated to leaf S in 2015 ($r = 0.69$; $P = 0.014$), whereas fruit Mg was correlated to leaf Mg in 2016 ($r = 0.73$; $P = 0.007$).

Correlation between yield and soil pH and nutrients. In 'Duke', yield was negatively correlated to soil pH in 2008 ($r = -0.35$; $P = 0.0001$), and positively correlated in 2010 ($r = 0.28$; $P = 0.0021$) and 2011 ($r = 0.36$; $P < 0.0001$). Yield of 'Duke' was negatively correlated to several soil nutrient levels measured in the autumn of the same year, including NO₃-N (2011–12) and NH₄-N (2010), P (2013), K (2011–12, 2014), Ca

and Mg (2008), Fe (2012), B (2010), Mn (2012), and Zn (2013) (data not shown). In contrast, yield was positively correlated to soil K and B measured in the same year in 2008 and soil Al in 2010 and 2012–13 (data not shown). Similar results were found when yield was compared with soil nutrient levels measured in autumn of the previous year, including negative correlations between yield and soil NO₃-N (2009–10, 2012) and NH₄-N (2009), P (2009–12, 2013), K (2012–14), Mg (2014), Fe (2012–13), B (2012), Mn (2009, 2011, 2013), and Al (2012), and a positive correlation between yield and soil Al (2011, 2014); however, yield was positively correlated to soil Ca (2013) and Fe (2014) measured in the previous year (data not shown).

Correlations between leaf nutrients and yield. Leaf N was negatively correlated to yield (in the same year) in 2009, 2011 ('Liberty' only), and 2014 ('Duke' only), and positively correlated to yield in 2015 and 2016 ('Liberty' only) (Fig. 10A and B).

Leaf P was also negatively correlated to yield in 6 out of 9 years in 'Duke' and 3 out of 9 years in 'Liberty' and positively correlated to yield in 1 year in 'Duke' (data not shown). The relationship between yield and leaf K was variable in 'Duke', with a positive correlation between the two variables during the first fruiting season in 2008 ($r = 0.271$; $P = 0.026$) and a negative correlation in 2009 ($r = -0.484$; $P < 0.0001$; data not shown) and 2011–14 (Fig. 10C). In contrast, leaf K in 'Liberty' was negatively correlated to yield in 2011, and positively correlated to yield in 2015–16 (Fig. 10D). Leaf Ca in 'Duke' was positively correlated to yield in all years of the study except for 2008 (negatively correlated), but no correlation was found in 'Liberty' in any year (data not shown). Leaf B was positively correlated to yield in 'Duke' in 2009–11 and in 'Liberty' in 2010 but was negatively correlated to yield in 'Duke' in 2008 and in 'Liberty' in 2012 and 2014 (data not shown). Leaf Cu was positively correlated to yield in both cultivars in 3 years of

Fig. 6. Effect of fertilizing with low (29–73 kg·ha⁻¹ N per year) or high (57–140 kg·ha⁻¹ N per year) rates of feather meal or fish solubles when mulched with sawdust, yard-debris compost topped with sawdust (compost + sawdust) or weed mat on leaf N concentration in (A) 'Duke' and (B) 'Liberty', leaf P in (C) 'Duke' and (D) 'Liberty', and leaf K in (E) 'Duke' and (F) 'Liberty' for northern highbush blueberry plants grown in a certified organic planting at Oregon State University's North Willamette Research and Extension Center from the first through the tenth growing season. Means are averaged over planting method (raised beds and flat ground) and 10 years (2007–16). Error bars represent ±1 se.

the study, as was leaf Al for 3 years in 'Liberty' and for 4 years in 'Duke' (data not shown).

Discussion

Mulch effects. In the later years of our study, soil organic matter was lowest with weed mat (2.9%) and highest with compost + sawdust mulch (4.1%). Organic soil amendments like compost that are resistant to decomposition, with a lower C:N ratio, are better suited to building soil organic matter than sawdust (Crohn, 2016), as we found. Declines in organic matter under black weed mat have been reported in other perennial crops (Atucha et al., 2011; Choi et al., 2011; Neilsen et al., 2003b). Soil organic matter probably decomposes more rapidly under

weed mat due to higher soil temperatures (Larco 2010; Strik et al., 2017a), as noted by others under black geo-textile or plastic (Cox, 2009; Runham et al., 2000; Strik et al., 2006). In general, higher levels of soil organic matter improve plant growth and yield in blueberry, but the presence of weeds in unmulched, control plots can confound the results (Clark and Moore, 1991; Goulart et al., 1997; Karp et al., 2006; Kozinski, 2006; Krewer et al., 2009; Savage, 1942; White, 2006). In this study, weeds were controlled in all treatments, allowing for a direct comparison of mulch effects (Strik, 2016; Strik et al., 2017a; Strik and Vance, 2017). Despite the measured differences in soil organic matter among the mulches in our trial, there was no impact on yield after 10 years (Strik et al., 2017a), indicating that all

treatments were within an acceptable range for blueberry.

Yard-debris compost is relatively high in pH (Sullivan et al., 2015, 2018) and, therefore, increased soil pH relative to sawdust mulch in the present study. Other types of composts also increase soil pH in blueberry (Burkhard et al., 2009; Forge et al., 2013). Hence, the use of compost can mitigate the decline in soil pH that occurs with fertilization with ammonium sources of N over time (Larco et al., 2013a; Strik, 2016). Although soil pH varied with mulch treatment, all remained within the desirable range for blueberry (4.5–5.5; Hart et al., 2006), likely explaining why there was little correlation observed between soil pH and yield in this study. However, even though the range was narrow in this study, soil pH was negatively

Fig. 7. Effect of fertilizing with low ($29\text{--}73\text{ kg}\cdot\text{ha}^{-1}\text{ N}$ per year) or high ($57\text{--}140\text{ kg}\cdot\text{ha}^{-1}\text{ N}$ per year) rates of feather meal or fish solubles on the Ca concentration of leaves sampled in late July to early August, depending on year, for northern highbush blueberry plants grown on (A) raised beds and (B) flat ground. The plants were grown in a certified organic planting at Oregon State University's North Willamette Research and Extension Center from the first through the tenth growing season (2007–16). Means are averaged over a combination of two cultivars (Duke and Liberty) and three mulch (sawdust, compost + sawdust, and weed mat) treatments. Error bars represent ± 1 SE.

correlated to leaf Mn in 6 out of 9 years, confirming leaf testing is a useful tool for signaling soil pH changes over time (Strik and Vance, 2015; Strik et al., 2017b). Neilsen et al. (2003b) reported a positive correlation between cumulative yield of apple and soil pH and a negative correlation between yield and soil Mn.

Over the course of the study, from establishment of the planting in Oct. 2006 through the end of the tenth growing season in 2016, application of sawdust as a mulch added a cumulative total of 261, 28, 88, and 217 $\text{kg}\cdot\text{ha}^{-1}$ of N, P, K, and Ca, respectively (Table 1). Yard-debris compost provided additional totals of 2274, 400, 961, and 2744 $\text{kg}\cdot\text{ha}^{-1}$ of each nutrient, respectively, compared to the use of sawdust mulch alone. Adding compost to the mulch increased the concentration of K in the soil by as much as 90% relative to sawdust only or weed mat (340–400 ppm and 200–240 ppm, on average, respectively) and increased soil P, Ca,

and Mg relative to using just sawdust mulch. Virtually all of the K, and most of the Ca and Mg in the compost was likely present in nonorganic (mineral) form at application (Crohn, 2016; Sullivan et al., 2015). After application, compost minerals (e.g., carbonates) react with acid soils to release plant-available nutrients. For example, Costello et al. (2019) demonstrated an increase in soluble nutrients when composts (pH 7.2) were acidified to pH 5.3 by addition of elemental sulfur. The impact of mulch and associated changes in soil nutrients on leaf nutrient status varied by treatment.

Although leaf N concentration was higher with compost in many cases, it did not lead to higher yield in the planting (Strik et al., 2017a). Forge et al. (2013) also reported increased leaf N of blueberry when using a yard-debris compost as a mulch. However, mulches containing compost or biosolids have had limited effect on leaf N concentration in other studies, including one on high-

bush blueberry (Burkhard et al., 2009; Neilsen et al., 2003a, 2007).

Leaf P concentration also increased with addition of compost mulch when the plants were fertilized with fish solubles in 'Duke', but not in 'Liberty'. In apple (*Malus $\times$ pumila* Mill.), a mulch of paper and biosolids increased leaf P in most years of a 6-year study (Neilsen et al., 2003a), but Forge et al. (2013) reported no effect of a yard-debris compost on soil or leaf P levels of blueberry in a 3-year study.

Compared with other mulches, the use of sawdust mulch led to the lowest levels of soil P, K, Mg, and Ca by the end of the study. The impact of sawdust mulch on leaf nutrient concentration relative to the other mulches varied with planting method and fertilizer treatment. For example, when the plants were grown on flat ground, leaf Ca was greater with sawdust mulch, on average, than with the other mulches in both cultivars, agreeing with Forge et al. (2013). When plants were young in this trial, mulching with sawdust reduced top growth and increased root growth relative to the other mulches (Larco et al., 2013a, 2013b), likely due to immobilization of N in the fertilizers reducing plant-available N (White, 2006).

Compared with sawdust mulch, which was the industry standard when this study was initiated, weed mat increased soil pH and the level of soil P, K, Ca, and Mg by the end of the study. In contrast, Choi et al. (2011) reported lower soil pH, P, K, Ca, and Mg under weed mat than wood chip mulch. In the present study, despite weed mat treatments receiving the same fertilizer as those mulched with sawdust, the soil under weed mat retained higher levels of the aforementioned nutrients likely in part due to less movement of these nutrients through the rooting zone with rainfall as compared with the organic mulches. In our climate, most rainfall occurs from October through May (U.S. Dept. of Interior, 2014). During the growing season, however, plots with weed mat required more irrigation each year (244–446 L/plant) than those mulched with sawdust to maintain a similar level of soil water content among the treatments (Strik et al., 2017a). A reduction in soil moisture under weed mat relative to organic mulch was also reported in apple (Choi et al., 2011).

We measured higher levels of soil $\text{NO}_3\text{--N}$ in plots with weed mat than those with other mulches, particularly on raised beds, which had higher soil temperatures than flat ground (Larco, 2010; Strik et al., 2017a). Choi et al. (2011) also measured higher $\text{NO}_3\text{--N}$ in weed mat plots compared with wood chip mulch. Higher levels of macronutrients in the soil under weed mat mulch led to corresponding increases in leaf N, P, and K (compared with sawdust mulch only) but had no effect on leaf Ca or Mg. Increases in leaf N may have been related to increased uptake with greater top growth or canopy size, whereas increased leaf P may have been a result of improved soil temperature during periods of root growth (Bryla et al., 2017; Valenzuela-Estrada et al.,

Fig. 8. Effect of fertilizing with low (29–73 kg·ha⁻¹ N per year) or high (57–140 kg·ha⁻¹ N per year) rates of feather meal or fish solubles when mulched with sawdust, yard-debris compost topped with sawdust (compost + sawdust) or weed mat on leaf Ca concentration for plants grown on (A) raised beds and (B) flat ground and leaf Mg concentration for plants grown on (C) raised beds and (D) flat ground. The northern highbush blueberry plants were grown in a certified organic planting at Oregon State University's North Willamette Research and Extension Center from the first through the tenth growing season. Means are averaged over a combination of two cultivars (Duke and Liberty) and 10 years (2007–16). Error bars represent ± 1 SE.

2011). Despite high levels of soil K, Ca, and Mg under weed mat mulch, it is possible that the ratio of these nutrients was not ideal or that the levels were sufficient. Blueberry plants have a low requirement for Ca (Korcak, 1988). Plants grown with weed mat may have had more top growth than those grown with other mulches, diluting the concentration of Ca and Mg in leaves, as was reported in cherry (*Prunus avium* L.; Yin et al., 2007). Weed mat mulch improved top growth of the plants during establishment (Larco et al., 2013a) and led to a 11% higher cumulative yield than the organic mulches during the study period, but only in 'Liberty' (Strik et al., 2017a). Krewer et al. (2009) reported that rabbiteye blueberry (*V. virginiana* Ait.) plants had greater leaf N with weed mat than sawdust mulch in the first year after planting only, and thereafter, the opposite was found. However, in their study, plants grown with weed mat had a lower yield.

The addition of compost or biosolids to a mulching program often increases soil and leaf K of blueberry and other crops (Burkhard et al., 2009; Forge et al., 2013; Neilsen et al., 2003a; 2007). In the present study, soil K increased with planting age and was positively correlated with leaf K concentration. However, both soil and leaf K levels were negatively correlated to yield in 3 and 5 out of 9 years, respectively, in 'Duke'. While some suggest that yield should be considered when interpreting leaf K concentration (e.g., Eck,

1988; Retamales and Hancock, 2012), because fruit are high in K (e.g., Strik and Vance, 2015), we found no evidence of this in these cultivars nor have others (Eck, 1988; Hancock and Nelson, 1988). Eck (1983) found that yield was positively correlated to soil K in a 10-year study on 'Bluecrop' blueberry, and when he applied various rates of K fertilizer, the highest yield was found when leaf K was between 0.45% and 0.55%. In that study, the plants may have responded positively to K fertilizer because soil K was relatively low at the site. Hancock and Nelson (1988) reported an optimal leaf K of 0.43%. In our study, we found the highest yields at leaf K concentrations ranging from 0.42% to 0.55%, although concentrations as high as 0.67% were measured.

Although ideal ratios of cations are promoted by some analysis laboratories, advisors, or consultants, neither our findings nor the data of others (Kopittke and Menzies, 2007) support this concept. Despite higher levels of Mg and Ca in the soil with addition of compost to the mulch, there was no increase in leaf Mg or Ca in the present study. In apple, biosolids and paper mulch increased soil Ca and Mg, as well as leaf Ca (Neilsen et al., 2003a). In our study, the ratios of Ca:K and Mg:K (ppm) were reduced to 5.8 and 1.5, respectively, when compost was added to the mulching program. Gough (1994) considered a Ca:K ratio of 5 to be desirable for blueberry. However, we found that soil Ca:K ratios

more than 5.8 to 6.3 (ppm; measured in compost + sawdust or with the high rate of fish) were associated with the lowest yields, whereas ratios of 8.3 to 8.8 (measured with weed mat mulch or with feather meal) led to the highest yield.

Several studies have reported that high levels of soil K reduce leaf Ca and Mg in blueberry (Eck, 1988; Fageria, 2001; Krewer and Ruter, 2012). We also found that high soil K reduced leaf Ca and noted negative correlations between these variables in 7 out of 9 years in 'Duke' and 4 years in 'Liberty'. Leaf Ca, on the other hand, was positively correlated to yield in all but one year of the study in 'Duke', as well as in a previous study by Eck (1977). The relationship between leaf Ca and yield in 'Duke' was likely a function of soil K and its negative impact on Ca uptake in blueberry. High soil K also reduced leaf Mg in 4 out of 9 years in both cultivars.

Raised beds vs. flat ground. Plants grown on raised beds had higher leaf N, P, and K, and lower Ca, Mg, and B, on average, than when plants were grown on flat ground. Leaf Ca and Mg may have been lower on raised beds (despite higher soil Ca and Mg, depending on fertilizer source), because the plants had more top growth [measured during establishment (Larco et al., 2013a) and evidenced by higher yield (Strik et al., 2017a)] and, therefore these nutrients were diluted in the leaves. Although soil P was unaffected by planting method and levels of P in soil were

Fig. 9. Relationship between leaf K and Ca concentration for 'Duke' (A) and 'Liberty' (B) northern highbush blueberry plants grown in a certified organic planting at Oregon State University's North Willamette Research and Extension Center. Each point represents the leaf nutrient concentration in the same year for a plot. Only years with a significant correlation are shown ($P < 0.05$). Actual P values and Pearson's correlation coefficients are given in the legend.

sufficient in all treatments, improved root growth on raised beds (Bryla et al., 2017; Valenzuela-Estrada, et al., 2011) likely increased leaf P as well as the other aforementioned nutrients.

Fertilizer source and rate. We previously reported that cumulative yield (2008–16) in this trial was 10% greater with feather meal than with fish solubles, on average, and 4% greater with the low rate than with the high rate of N fertilizer (Strik et al., 2017a). 'Duke' was particularly sensitive to fertilizer source, producing 35% less yield overall with fish solubles than with feather meal. In contrast, there was relatively little effect of fertilizer source or rate on yield in 'Liberty'. Here, we show evidence that the high rate of N was in excess of the nutrient needs of the plants. Fertilizing with the high rate of N throughout the study period (Table 2) increased soil $\text{NO}_3\text{-N}$ level, particularly when using fish solubles (with sawdust or compost + sawdust mulch) or with feather meal (with weed mat mulch). Soil $\text{NH}_4\text{-N}$ was also high when fertilizing with fish solubles and

mulching with weed mat. Leaf N concentration was higher when fertilizing with fish solubles, particularly at the high rate in all mulch treatments when plants were young, and at either rate throughout the study in the sawdust or compost + sawdust mulches. Nitrogen in the fish solubles may have been more available in the sawdust or compost + sawdust mulches than the granular source of feather meal, as both fertilizers were applied on top of the mulches. In contrast, the weed mat was opened before applying the granular feather meal and the drip irrigation underneath the weed mat coupled with increased temperatures (Larco 2010; Strik et al., 2017a) may have increased the availability of N in the feather meal, leading to fewer effects of fertilizer source on leaf N in this mulch treatment. We also found that when feather meal was first applied in early April of the first growing season (2007), plants showed symptoms of N deficiency, and growth was reduced (Larco et al., 2013a, 2013b). Most fertilizer N is acquired during shoot and fruit development (Bañados, 2006; Bañados et al.,

2012; Retamales and Hanson, 1989; Throop and Hanson, 1997), thus fertilizer N must be applied early enough to be available to the plant when needed. When the first application of feather meal was applied earlier (early March) of the following years (2008–16), no symptoms of N deficiency were observed (Larco et al., 2013a, 2013b; Strik et al., 2017a). However, leaf N concentration was still lower with feather meal than with fish solubles in many years. Nitrogen applied through fertigation, as was done with the fish solubles in our study, has been shown to be more readily available than granular sources in blueberry (Bryla and Machado, 2011). Furthermore, feather meal was applied in the split applications in early March and early May each year, whereas the fish solubles were applied by fertigation every 2 weeks from mid April to early July, likely increasing availability of N in the root zone.

Higher rates of N fertilizer application, regardless of source, increased leaf N, thus confirming what has been reported in conventional production systems in blueberry (Bañados, 2006; Bañados et al., 2012; Bishop et al., 1971; Cummings et al., 1971; Eck, 1977; Spiers, 1983; Townsend, 1973). However, the higher leaf N measured with fish solubles did not result in a higher yield. Across all fertilizer treatments, there was no consistent relationship between yield and leaf N concentration in the same year over the study period.

Higher rates of N fertilizer increased fruit N concentration of 'Wolcott' (Ballinger and Kushman, 1966), but no such response was found in six cultivars of highbush blueberry grown conventionally in Oregon (Strik and Vance, 2015). Although the fruit N concentration varied between years in certified organic blueberry in Oregon, there was no cultivar (six studied) by year interaction, and the plantings were fertilized at the same rate of N between years (Strik and Vance, 2015). In this study, we found no consistent relationship between the concentration of N in the fruit and leaves. In contrast, Ballinger and Kushman (1966) found that increased yield reduced leaf and fruit N concentration.

These organic fertilizers also contain many nutrients other than N. For example, fertilization with the high rate of fish solubles increased the application of P, K, and Mg by 161, 663, and 25 $\text{kg}\cdot\text{ha}^{-1}$, respectively, and decreased Ca by 79 $\text{kg}\cdot\text{ha}^{-1}$ compared with same rate of feather meal over the whole study period (Table 2). Although the fish solubles contained high levels of Na (1.9% to 2.2%) and had an EC of 20–25 $\text{dS}\cdot\text{m}^{-1}$, the product was diluted before application to reduce the EC to levels well below the 2 $\text{dS}\cdot\text{m}^{-1}$ threshold reported by Bryla and Machado (2011), as confirmed by measurements of the soil solution during the study (Valenzuela-Estrada, unpublished data).

Fertilization with the high rate of fish solubles increased leaf P concentration during many years of the study. Although higher rates of fertilizer N have been shown to

Fig. 10. Relationship between yield per plant and leaf N concentration for 'Duke' (A) and 'Liberty' (B) and leaf K concentration for 'Duke' (C) and 'Liberty' (D) northern highbush blueberry plants grown in a certified organic planting at Oregon State University's North Willamette Research and Extension Center. Each point represents the yield and leaf nutrient concentration in the same year for a plot. Only years with a significant correlation are shown ($P < 0.05$). Actual P values and Pearson's correlation coefficients are given in the legend.

increase leaf P in conventional production systems (Bryla et al., 2012; Spiers, 1983), we did not observe this response with feather meal, which contained very little P.

Although the use of fish solubles at either rate increased soil K during most of the study period, there was no consistent relationship between the rate or source of fertilizer nutrient applied and soil Ca, Mg, and B. Fertilizing with fish solubles and mulching with compost + sawdust led to the highest soil K. Perhaps, the main reason why 'Duke' did not yield well when fertilized with fish solubles was the high amount of K in the product. High levels of soil K from the fertilizer led to increased leaf K and reduced leaf Ca and Mg concentrations in both cultivars. The negative correlation between yield and leaf K (and correlated impacts) was more prevalent in 'Duke' than in 'Liberty', but the direct reasons for the difference between the cultivars are not known.

Feather meal was a good source of Ca for the plants and increased leaf Ca relative to using fish solubles. Growers are very interested in increasing fruit Ca to improve berry firmness (Saure, 2005; Van-Buren, 1979) and often assess leaf Ca concentration as an indicator of potential fruit quality. Although Strik and Vance (2015) found considerable variation in leaf and fruit Ca concentrations, there did not appear to be a relationship in these values for either cultivar. In addition, foliar applications of Ca at manufacturer

recommended rates have not been found effective to increase fruit Ca concentration (Arrington and DeVetter, 2017; Vance et al., 2017), likely due to the relatively short time that stomates are functional in blueberries and the impact on Ca uptake through the xylem (via transpiration) in the fruit (Yang, 2018). Although the use of feather meal increased fruit Ca concentration in this trial relative to fish solubles (Fernandez-Salvador, unpublished data), the relationship between leaf and fruit Ca concentrations was inconsistent with both negative and positive correlations in 'Liberty' and 'Duke', respectively, in 1 out of 2 years.

Leaf Ca was negatively correlated to leaf N in many years of the study, perhaps because more Ca was applied with feather meal than with the fish solubles, whereas the latter source increased leaf N. Leaf Ca increased with plant age from establishment to maturity in both cultivars, but leaf N concentration was higher in young plants than mature plants. Conventional blueberry studies showed that leaf Ca declined with higher rates of N application, but that the leaf N increased (Bishop et al., 1971; Eck, 1977; Spiers, 1983; Townsend, 1973). In contrast, leaf Ca increased with rate of N fertilization in 1 year of a 2-year study of conventionally-grown 'Bluecrop' in Oregon (Bryla et al., 2012), likely due to decreased plant growth at the highest rates of N fertilizer applied and associated higher leaf Ca.

Boron application was increased over the course of the study when fish solubles were used as a fertilizer source. Compared with feather meal, fertilizer source only affected leaf B when plants were young, and in those years, leaf B concentration was higher with feather meal. Bryla et al. (2012) reported that higher rates of N application reduced leaf B in 1 of 2 years. There were no consistent fertilizer source or rate effects on leaf Cu or Zn in either cultivar, despite large differences between the products and rates used.

Fertilization with the high rate of either source significantly reduced soil pH over the course of the study. This effect could cause low pH issues in a longer-term planting. Fertilization with the high rate of fish solubles, in particular, increased leaf Mn, likely a response to the lower soil pH.

Cultivar. Cultivar had a large impact on leaf nutrient concentration, with 'Liberty' having lower levels of N, P (most years), K, Ca (although dependent on mulch treatment), Mg, S, B, Cu, Zn, and Al and higher levels of Fe and Mn than 'Duke', on average, and had higher yield (Strik et al., 2017a). Our results confirm the importance of leaf tissue sampling cultivars separately when assessing plant nutrient status (Hart et al., 2006; Strik and Vance, 2015).

Leaf nutrient testing. Although leaf analysis is a common practice to assess plant nutrient status and adjust fertilizer programs, as needed, the only consistent association

with yield over the length of this study was for leaf Ca (positive) and P and K (negative) in 'Duke'. Despite having typical commercial yields, particularly for the best production system treatments (Strik et al., 2017a), leaf N and P were below published sufficiency levels in many years of our study (Hart et al., 2006). However, leaf P was positively correlated to yield for 3 years only in 'Liberty' and was negatively correlated to yield in most years of the study in 'Duke'. In addition, despite the negative correlation between leaf K concentration and yield, particularly in 'Duke', leaf K was only above current sufficiency levels in 1 year for both cultivars (2008) and was below sufficiency in 'Liberty' in 1 year. Although higher concentrations of leaf K were correlated with lower leaf Ca and Mg, these latter nutrients were only below sufficiency levels in one of the study years. Strik and Vance (2015) proposed that the sufficiency levels for N and P could be lowered, without negative effect on plant performance, in organic production systems as compared with conventional. They also suggested that the current leaf concentration standards for K may need to be reduced based on levels commonly measured in high-performing commercial fields. Our results here confirm these recommendations, particularly to reduce the risk of growers applying excess K fertilizer to achieve higher leaf K levels and considering the negative impact this may have on yield and potentially uptake of other cations.

Leaf B concentrations were below sufficiency levels the entire study period, despite sufficient or close to sufficient levels of soil B and application of additional fertilizer B as a granular to the soil and as a foliar product just before bloom according to the recommended practice (Hart et al., 2006). Although sufficient plant levels of B are thought to be critical for good pollination and fruit or seed set, frequent applications of foliar B, while improving leaf and fruit B concentrations in some cases, had no impact on fruit set or yield in Washington (Arrington and DeVetter, 2017). In our study, leaf B was not consistently related to yield. Leaf and soil Cu levels were below sufficiency (Hart et al., 2006; Horneck et al., 2011) in most years of the study. Strik and Vance (2015) speculated that the sufficiency levels for Cu may have been originally established as higher than needed due to common use of Cu fungicides in blueberry. Copper fungicides were not needed or used during this study.

Conclusions

Testing these various production systems in a long-term certified organic trial from planting to maturity validated that establishing blueberry plants on raised beds rather than flat ground is critical for maximizing plant growth (Larco et al., 2013a) and yield (Strik et al., 2017a). Plants on raised beds have better root growth (Bryla et al., 2017; Valenzuela-Estrada, et al., 2011) and, as shown here, improved plant nutrient status.

Choice of a mulch is also important, both economically and for weed control. Weed mat mulch was the most economic method of controlling weeds (Strik and Vance, 2017) and increased cumulative yield as much as 11% (Strik et al., 2017a). However, disadvantages of using weed mat include increased irrigation requirement and presence of voles (*Microtus* sp.) (Strik et al., 2017a), and the significant decrease in soil organic matter reported here. Although the organic matter had not been reduced to a level detrimental to yield (through 2016), this is of concern for longer-term production. Adding a layer of sawdust under the weed mat showed great promise for mitigating some of these negative effects of weed mat mulch alone in organic production (Strik et al., 2017b) and is showing positive results for plant growth and early production during blueberry plant establishment in conventional production (Strik, unpublished data).

Organic growers like to use compost as a slow-release source of N; however, having a yard-debris compost regularly applied to the planting, as was done here with compost + sawdust, may not be a sustainable option. As a mulch, compost topped with sawdust added considerable weed management costs compared with sawdust mulch alone (Strik and Vance, 2017). Although the addition of yard-debris compost to the mulch improved the level of soil organic matter compared with sawdust mulch alone, the compost increased soil K, leading to increased leaf K and decreased leaf Ca and Mg.

Plants in our study performed better ('Duke') or similarly ('Liberty') when fertilized with the lower rate of N than with the higher rate (Strik et al., 2017a). Fertilization with fish solubles, the most common fertilizer source used in organic blueberry plantings when the study began (Strik, 2016), led to higher K levels, decreasing yield of 'Duke'. Considering the high cost of these organic fertilizers (Strik et al., 2017a), our current N rate recommendations (Hart et al., 2006) may be reduced in organic production, particularly when using a high proportion of fertilizer sources containing K as well as N.

It is clear in these organic production systems that assessing plant nutrient status and management of fertility programs is complicated. There were large interactions among treatments, indicating that making broad or general recommendations for growers is not advisable. For example, the mulch used affected plant response to fertilizer source and rate, and cultivars differed in their response. 'Duke' was particularly sensitive to fertilization with high rates of fish solubles. Because organic fertilizer sources of N most typically contain other nutrients, our study illustrates the importance of careful fertility management to avoid nutrient imbalances. Fertilizers and composts should be carefully chosen and likely changed over time to avoid large shifts in soil or nutrient availability. Although soil and leaf tissue testing are important to help manage fertilizer programs, the lack of a consistent relation-

ship between soil and plant nutrient status and yield was a reflection of the complicated interactions that occurred among nutrients in these organic production systems. Clearly, careful observations of plant growth and yield and awareness of some of the pitfalls associated with long-term use of composts and a particular fertilizer source are important.

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