Nonchemical, Cultural Management Strategies to Suppress *Phytophthora* Root Rot in Northern Highbush Blueberry

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Abstract. *Phytophthora cinnamomi* Rands causes root rot of northern highbush blueberry (*Vaccinium corymbosum* L.), which decreases plant growth, yield, and profitability for growers. Fungicides are available to suppress the disease, but are prone to development of resistance in target pathogens and cannot be used in certified organic production systems. Alternative, nonchemical, cultural management strategies were evaluated to reduce phytophthora root rot in a field infested with *P. cinnamomi*. The field was planted with ‘Draper’ blueberry, which is highly susceptible to the pathogen. The soil was either amended with gypsum or not before planting, and the plants were irrigated using narrow (adjacent to plant crown) or widely spaced (20 cm on either side of the plant crown) drip lines and mulched with douglas fir sawdust or black, woven geotextile fabric (weed mat). A fungicide control treatment was also included in the study and consisted of applying two conventional fungicides, mefenoxam and fosetyl-Al, to plants irrigated with narrow drip lines and mulched with sawdust. Initially, root infection by *P. cinnamomi* was lower with the combination of gypsum, wide drip lines, and sawdust mulch than with any other treatment, except the fungicide control. The soil under weed mat accumulated more heat units than under sawdust and resulted in faster hyphal growth by the pathogen. However, plant growth was similar in both mulch types. The effects of drip line placement and gypsum, on the other hand, were interactive, and plants grown with a combination of wide drip lines and gypsum produced the greatest amount of biomass among the cultural treatments. Narrow drip lines negated the disease-suppressive effects of gypsum by moving zoospore-inhibiting Ca^{2+} away from the plant root zone, and also resulted in wetter soil near the crown of the plants, which likely promoted zoospore discharge and root infection. However, wide drip lines resulted in N deficiency symptoms during the first year after planting and, therefore, resulted in less plant growth than the fungicide control. Thus, if N is managed properly, this study suggests that concerted use of gypsum and wide drip lines can help suppress phytophthora root rot in northern highbush blueberry and increase production in field soils where the pathogen is present.

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Phytophthora cinnamomi Rands is a soil-borne pathogen that causes root rot in >900 plant species worldwide, including northern highbush blueberry (Zentmyer, 1980). Currently, there are two groups of fungicides (phenylamides and phosphonates) registered for root rot control in blueberry, including mefenoxam and fosetyl-Al (Brannen et al., 2009). Unfortunately, the risk of developing fungicide resistance is very high in *Phytophthora* species, especially to mefenoxam (Hu et al., 2010). In addition, organic blueberry production is increasing rapidly, but neither

of these chemicals is certified for use on organic crops (DeVetter et al., 2015). Pre-plant soil fumigation is also an option for managing root rot. However, it is expensive, not widely used in the industry, and there is little evidence for its effectiveness against this disease in blueberry production systems. The risk of crop loss from *P. cinnamomi* may increase substantially without fungicides; therefore, disease-suppressive cultural practices are needed for both conventional and organic blueberry systems.

Organic mulches (e.g., sawdust or bark) have been shown to suppress soil populations of *P. cinnamomi* in eucalyptus (*Eucalyptus* sp. L’Hér.), fraser fir [*Abies fraseri* (Pursh) Poir.], and avocado (*Persea americana* Mill.) plantings (Downer et al., 2001; Menge et al., 1994; Richter et al., 2011a). The cell walls of *Phytophthora* hyphae are largely composed of glucans, and glucanase activity associated with the microbes in organic mulches may cause hyphal lysis and sporangial abortion (Downer et al., 2001; Richter et al., 2011b). Historically, most blueberry fields were mulched with sawdust or bark chips (Strik and Yarborough, 2005). However, many new fields are mulched with geotextile fabrics, often referred to as “weed mat.” Weed mat is more economical for weed control than sawdust, particularly in organic systems, and the use of it may result in greater plant growth and yield in blueberry (Julian et al., 2012; Larco et al., 2013). Most growers use black weed mat, which increases soil temperature during sunny days, especially when there is little shade under the canopy such as early in the season and in new plantings (Larco, 2010). Root infection by *P. cinnamomi* has been shown to be more severe when soil temperature exceeds 25 °C (Erwin and Ribeiro, 1996). Therefore, it is possible that weed mat may increase the incidence of phytophthora root rot in blueberry.

The zoospore infection cycle of *P. cinnamomi* requires nearly saturated soil moisture conditions (de Silva et al., 1999). Consequently, infection is readily affected by heavy rain or irrigation and is often greater when plants are irrigated by drip irrigation than by sprinklers or microsprinklers, which results in increased soil water content near the plant crown (Bryla and Linderman, 2007). Whereas most blueberry fields were historically irrigated by sprinklers, many are now irrigated by drip because of concerns for food safety and efforts to increase water use efficiency (Bryla et al., 2011). Many blueberry growers use two lines of drip tubing per row, with one line placed on either side of the plant (Ehret et al., 2012). The drip lines are usually placed near the plant crown during the first year or two after planting and are later moved 15–20 cm from the crown, once the root system develops (Bryla and Strik, 2015). However, given the propensity for developing root rot in wetter soils, Bryla and Linderman (2007) suggested that blueberry plants might benefit from a wider drip line spacing immediately after planting,

particularly if the soil is already infested with *P. cinnamomi*.

Soil amendment with calcium may also suppress phytophthora root rot (Menge et al., 1994; Messenger et al., 2000a; Pinkerton et al., 2009). A high level of calcium in the soil inhibits zoospore motility of the pathogen and thereby disrupts the infection process (Messenger et al., 2000b). Greenhouse assays suggested that gypsum may be useful for reducing phytophthora root rot in northern highbush blueberry (Yeo, 2014). Gypsum provides more soluble Ca^{2+} than carbonate sources such as lime and does not increase soil pH appreciably (Shainberg et al., 1989). High soil pH is deleterious to many ericaceous plant species, including northern highbush blueberry, which is adapted to soil pH in the range of 4.5–5.5 (Hart et al., 2006).

The objective of the present study was to evaluate the effects of mulch type, drip line placement, and gypsum on phytophthora root rot in northern highbush blueberry. The study was carried out in a new planting, as young plants are usually the most susceptible to root rot (Bryla and Linderman, 2007).

Materials and Methods

Study site. The study was located at the Oregon State University Lewis Brown Horticultural Research Farm in Corvallis, OR (lat. 44°33'10"N, long. 123°13'9"W, 68 m elevation). Soil at the site is classified as a Malabon silty clay loam (fine, mixed, mesic Pachic Ultic Argixeroll). A soil test in Feb. 2012 indicated that the pH of the soil was 5.4, the cation exchange capacity was 24.4 $\text{cmol}\cdot\text{kg}^{-1}$, and Bray-P was 23 ppm (Kuo Testing Laboratories, Othello, WA).

Previously, the site was planted with 'Duke' northern highbush blueberry in 2004. The planting was removed in 2010 because of severe problems with phytophthora root rot (Bryla, 2006). After the planting was removed, the field was seeded with a cover crop mix of fava bean (*Vicia faba* L.), vetch (*Vicia sativa* L.), oat (*Avena sativa* L.), and clover (*Trifolium pretense* L.) in the fall of 2011. The cover crop was killed with glyphosate (2.24 kg a.i./ha) in Apr. 2012 and tilled into the soil using a 182-cm-wide power spader (Tortella, Ortona, Italy) to a depth of 30 cm on 9 May 2012. Douglas fir (*Pseudotsuga menziesii* Franco) sawdust (Lane Forest Products, Eugene, OR), aged for 1 year, was spread out in a 2.5-cm-thick layer across the field and incorporated with a 127-cm-wide rototiller (Howard Selectalith, Sorø, Denmark) to a depth of 15 cm. Eight raised beds were formed 0.3-m high and 1.0-m wide using a tractor-drawn bed shaper (Ernst Irrigation, St. Paul, OR). The raised beds were 45-m long (28° N – 208° S orientation) and centered 3.0-m apart. The areas between the raised beds were seeded with annual ryegrass (*Lolium multiflorum* Lam.), which was mowed regularly after establishment and went dormant in the summer.

To enhance uniform disease pressure, additional *P. cinnamomi* inoculum was incorporated into the soil in May 2012 after the beds were shaped. Inoculum was produced in fungal spawn bags with filter patches (Fungi Perfecti, Sheldon, WA). Twenty-seven bags were filled with 3 L of medium-grade vermiculite and 1.5 L of V-8 juice broth consisting of 10% V-8 juice (Campbell Soup Co., Camden, NJ) by volume and amended with 2 $\text{g}\cdot\text{L}^{-1}$ CaCO_3 . The bags were autoclaved for 55 min. After cooling, a 100-mm-diameter petri plate filled with potato dextrose agar (PDA) and fully colonized with a 10-d-old isolate of *P. cinnamomi* was sliced into 100 pieces and added to each bag. The isolate was obtained in 2010 from a 'Draper' blueberry plant infected naturally in a field located in Corvallis, OR (Vargas et al., 2015) and was successfully used in previous experiments to cause root rot (Yeo et al., 2016). Each bag was incubated in the dark at 20 °C and shaken at 2-week intervals. After 4 weeks, inoculum from all of the bags was homogenized in a cement mixer, and 1.56 kg of the resulting mixture was spread out in a 30-cm-wide band and incorporated 15-cm deep into each planting bed using a front-tine rototiller (Sears and Roebuck, Hoffman Estates, IL). The final density of the inoculum was 2.7 cfu per cm^3 of soil.

Treatments and experimental design. Nine treatments (eight cultural treatments and one fungicide control treatment) were applied to the center six beds in the planting on May 2012. The outer two beds in the planting served as nontreated borders. The treatments were arranged in a split-plot design with six replicate blocks (beds). Two mulch types (weed mat and sawdust) were randomly assigned as main plot treatments, and a combination of two drip line spacings (narrow and wide) and two gypsum levels (applied or not) were randomly assigned as subplot treatments (4.6-m long each), for a total of eight cultural treatments (two mulch types $\times$ two drip line spacings $\times$ two gypsum levels). A fungicide treatment (below) was also included in the study and was randomly assigned as a subplot within each of the sawdust main plots.

Gypsum ($\text{CaSO}_4\cdot 2\text{H}_2\text{O}$) was applied at a rate equivalent to 2.24 $\text{t}\cdot\text{ha}^{-1}$. The gypsum was spread out in a 0.3-m-wide band on the

beds and was incorporated 15-cm deep with a narrow front-tine rototiller (Sears and Roebuck, Hoffman Estates, IL). Mulch and drip lines were added to the beds after planting. A line of drip tubing (Toro Micro-Irrigation, El Cajon, CA) was installed on each side of the bed and secured either next to (narrow spacing) or 20 cm (wide spacing) from the plant crown using wire staples. The tubing had 1 $\text{L}\cdot\text{h}^{-1}$ in-line, pressure-compensating drip emitters spaced every 30 cm. Douglas fir sawdust mulch was applied ≈ 8 -cm deep on the beds using a side-discharge mulch spreader. Black weed mat (Berry Hill Drip Irrigation, Buffalo Junction, VA) was placed on each side of the beds and secured in place with wire staples; two strips were used and overlapped in the center of the bed. Slits were cut and folded under to create 15-cm-square openings in the weed mat for each plant.

The fungicide control treatment had no gypsum and was irrigated with narrow drip lines. The plots were treated with mefenoxam (Ridomil Gold SL; Syngenta Crop Protection, Greensboro, NC) and fosetyl-Al (Aliette WDG; Bayer CropScience, Research Triangle Park, NC). Mefenoxam was sprayed on the surface of the beds (45-cm-wide band) shortly after planting in May 2012 and again in May 2013 at a rate of 0.18 $\text{mL}\cdot\text{m}^{-1}$. Fosetyl-Al was sprayed on the fully expanded leaves of the plants in late May each year at a rate of 3.4 $\text{kg}\cdot\text{ha}^{-1}$ (0.62 g/plant).

The treatment plots were planted with 'Draper' northern highbush blueberry on 15 May 2012. 'Draper' was selected based on its susceptibility to *P. cinnamomi* (Yeo et al., 2016). The plants were obtained from a commercial nursery (Fall Creek Farm and Nursery, Lowell, OR) as 3-L container stock and spaced 0.76-m apart in the beds. Soil P was low at the site; therefore, triple superphosphate (0N–45P–0K) was mixed into each planting hole at a rate of 45 $\text{kg}\cdot\text{ha}^{-1}$ P before planting. Each treatment plot consisted of six contiguous plants, and each bed of treatments had two border plants on each end. The outer beds on either side of the planting were planted on the same date with 'Toro' and 'Reka' northern highbush blueberry.

Irrigation and nitrogen management. The field was initially irrigated daily with hand-set overhead sprinklers to establish the annual

Table 1. Effect of fungicide treatment on shoot and root dry weight and percent root infection of 'Draper' blueberry grown for 2 years (2012–13) in a field infested with *Phytophthora cinnamomi* in Corvallis, OR.^z

Fungicide	Shoot dry wt (g/plant)		Root dry wt (g/plant)		Root infection by <i>P. cinnamomi</i> (%) ^y	
	2012	2013	2012	2013	2012	2013
Yes ^a	175	332	72	130	15	4
No	111	94	34	31	22	10
Significance	***	***	**	***	NS	NS

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

^zThe plants were harvested destructively in December of each year. All plants were mulched with sawdust, irrigated with two drip lines located near the plant crown on each side of the bed, and in soil without gypsum amendment.

^yPercent of 20 (2012) or 10 (2013) root pieces infected by *P. cinnamomi*.

^aThe fungicide applications consisted of mefenoxam (0.18 $\text{mL}\cdot\text{m}^{-1}$, soil spray) and fosetyl-Al (3.4 $\text{kg}\cdot\text{ha}^{-1}$, foliar spray) in May 2012 and 2013.

ryegrass between the raised beds. Once the grass was established, overhead irrigation was discontinued, and drip irrigation was scheduled four times per week during the growing season using an automated irrigation controller. Irrigation was adjusted weekly based on plant size and reference evapotranspiration obtained from the Corvallis AgriMet agricultural weather station (<http://www.usbr.gov/pn/agrimet/>), as described previously by Bryla et al. (2011). The weed mat plots were irrigated with 20% more water than the sawdust plots during the first year after planting to compensate for greater plant water use with weed mat. Water use is initially greater with weed mat because of warmer soil and canopy temperatures (Larco, 2010). However, once the plants grow and shade the beds, extra water is no longer needed with weed mat.

Nitrogen fertilizers were applied by fertigation using a fertilizer injector (Dosatron International, Clearwater, FL) installed in the irrigation manifold. In 2012, the plants were fertigated with liquid ammonium sulfate (9N-0P-0K). That year, fertigation was initiated on 30 May and included four applications of 28 kg ha⁻¹ N every 2 weeks. The first two applications were injected at 2% by volume, but this concentration resulted in N deficiency (yellowing leaves) in the plants irrigated with wide drip lines because the roots in those plots were located too far from this relatively immobile N source. Therefore, the next two applications were reduced to 0.5% by volume, to slow the injection rate and potentially move more N and water through the soil during each fertigation event. The following year, the plants were fertigated with liquid urea (20N-0P-0K). Urea is much more mobile during fertigation than NH₄-N but readily converts to NH₄ within a few days after application (Haynes, 1990). The fertilizer was injected 10 times between 17 Apr. and 17 July at a rate of 18 kg ha⁻¹ N per application (1% by volume). There were no visual symptoms of N deficiency in the plants in 2013.

Measurements. Soil samples were collected for nutrient analysis using a 2-cm-diameter core sampler. The sampler was inserted 15-cm deep at six random locations near the center of the bed in each treatment plot in June 2012 and July 2013. Each set of samples was pooled, air-dried, ground, homogenized, and analyzed for soil pH [1 soil: 1 water (v/v)] and Mehlich III extractable cations at a commercial laboratory (Brookside Laboratories, New Bremen, OH). Leaves were also collected for nutrient analysis in early August each year. Four recently matured leaves were sampled from the center four plants in each plot, pooled, oven-dried at 70 °C, ground, and analyzed for N using a combustion analyzer (Model CNS-2000; LECO Corp., St. Joseph, MI) and for P, K, Ca, Mg, and S using an inductively coupled plasma optical emission spectrometer (Optima 3000DV; PerkinElmer, Wellesley, MA) after microwave digestion in 70% (v/v) nitric acid (Gavlak et al., 2005).

Soil water content was measured in each plot on 12 July and 7 Aug. 2013 using the Trase I time domain reflectometry system (Soilmoisture Equipment Corp., Santa Barbara, CA). The system was equipped with a 15-cm waveguide. The waveguide was inserted

vertically into the soil at three locations in each treatment plot. Each measurement was taken between plants in the center of the bed within 1–2 h after an irrigation event.

Hyphal growth of *P. cinnamomi* was measured in a subset of the sawdust and

Table 2. Effects of mulch type, drip line placement, and gypsum amendment on shoot and root dry weight of 'Draper' blueberry grown for 2 years (2012–13) in a field infested by *Phytophthora cinnamomi* in Corvallis, OR.^z

Treatment	Shoot dry wt (g/plant)		Root dry wt (g/plant)	
	2012	2013	2012	2013
Mulch				
Sawdust	96	106	43	36
Weed mat	86	85	45	41
Significance	NS	NS	NS	NS
Drip lines (D)				
Narrow	121	87	39	26
Wide	61	105	49	51
Significance	***	NS	*	***
Gypsum (G)				
No	84	78 b ^y	43	33
Yes	98	96 b	46	44
Significance	NS	D × G**	NS	NS

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

^zThe plants were harvested destructively in December of each year.

^yMeans followed by the same letter are not significantly different ($P \leq 0.05$).

Fig. 1. Effects of mulch type (A), drip line placement (B), and gypsum amendment (C) on root infection incidence (%) in 'Draper' blueberry grown for 2 years (2012–13) in a field infested by *Phytophthora cinnamomi* in Corvallis, OR. Roots were sampled from soil cores (●, ○) or from destructively harvested plants (■, □). An asterisk above the symbols on a given sampling date indicates the means are significantly different at $P \leq 0.05$.

Table 3. Soil heat units and hyphal growth of *Phytophthora cinnamomi* grown in situ on potato dextrose agar in sealed petri plates buried 5-cm deep under sawdust and weed mat for 7–10 d in a field of ‘Draper’ blueberry in Corvallis, OR.

	Soil heat units (°C) ^z			<i>P. cinnamomi</i> hyphal growth (cm ²) ^y		
	9–16 Aug. 2012	18–28 Apr. 2013	11–19 July 2013	9–16 Aug. 2012	18–28 Apr. 2013	11–19 July 2013
Mulch						
Sawdust	97	52	114	29.8	5.4	25.9
Weed mat	112	64	118	37.1	7.3	28.3
Significance	***	***	*	***	**	*

*, **, *** Significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

^zCalculated at a baseline of 9 °C (Zentmyer et al., 1976).

^yGrown in situ on petri plates buried 5-cm deep.

Table 4. Effects of mulch type, drip line placement, and gypsum amendment on soil water content in a field of ‘Draper’ blueberry infested by *Phytophthora cinnamomi* in Corvallis, OR.^z

Treatment	Soil water content (%)	
	July 2013	Aug. 2013
Mulch		
Sawdust	31.5	19.1
Weed mat	29.5	17.6
Significance	NS	NS
Drip lines (D)		
Narrow	36.4	22.9
Wide	24.5	13.8
Significance	***	***
Gypsum (G)		
No	31.2	18.8
Yes	29.8	17.9
Significance	NS	NS

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

^zMeasurements were taken at a soil depth of 0–15 cm.

weed mat plots. Single, 5-mm-diameter plugs of inoculum from the same isolate used to infest the field were aseptically transferred to new PDA petri plates under sterile conditions. The plates were wrapped with parafilm and placed in sealable plastic bags in two stacks of three per bag. The bags were buried 5-cm deep in three subplots of sawdust and weed mat with wide drip lines and no gypsum. The plates were buried on three separate dates, including 9 Aug. 2012, 18 Apr. 2013, and 11 July 2013. The plates were recovered 7–10 d after burial, and the diameter of each culture was measured to the nearest millimeter in two perpendicular directions. Soil temperature was also recorded next to the buried bags using waterproof temperature loggers (HOBO Pendant; Onset Computer Corporation, Bourne, MA). The readings were taken every 15 min, and heat units were calculated based on a minimum threshold of 9 °C (Zentmyer et al., 1976).

Root samples were collected from plots and assessed for infection for the eight cultural treatments on 26 July 2012 and on 25 Mar., 26 June, and 24 Sept. in 2013. The roots were removed by driving a 2-cm-diameter core sampler diagonally through the root zone of one plant/plot to a depth of 15 cm. Twenty (2012) or 10 (2013) 1-cm-long root pieces were randomly sampled from the cores, rinsed in 1% bleach solution (0.05% NaOCl) for 30 s, and placed onto petri plates filled with P₁₀ARPH agar. The agar is a semiselective medium for *Phytophthora* species (Tsao and Guy, 1977) and

contained 10 ppm pimarinic (Sigma-Aldrich, St. Louis, MO), 250 ppm ampicillin (Sigma-Aldrich), 10 ppm rifampicin (Sigma-Aldrich), 100 ppm pentachloronitrobenzene (Terrachlor, 75% a.i.; Chemtura, Middlebury, CT), and 25 ppm hymexazol (Tachigaren, 70% a.i.; Sankyo Co., Tokyo). The plates were incubated at 20 °C for 10 d and monitored periodically under a microscope (×400) to determine the percentage of the root sections infected by *P. cinnamomi*.

One plant from each treatment plot, including the fungicide controls, was harvested destructively in Dec. 2012 and 2013. The plants were selected randomly from either the north or south end of the plot and assessed for root infection following the same laboratory procedures mentioned above. In this case, the roots were washed with running tap water before collecting the 10 or 20 root pieces. Afterward, the plants were divided into root and shoots, oven-dried, and weighed.

Statistical analyses. Shoot and root dry weights, percent root infection, soil water content, soil pH, and soil and leaf nutrient concentrations were analyzed by mixed model analysis of variance using the PROC MIXED statement in SAS 9.2 (SAS Institute, Cary, NC). To homogenize the variances before analysis, percent root infection was transformed using arcsine of the square root of the proportion. Fixed effects in the model included mulch type, drip line spacing, gypsum amendment, and each interaction among the eight cultural treatments. Random effects included bed and bed × mulch interaction to account for the split-plot experimental design. The fungicide treatment was not included in this analysis as it was not a component of the 2 × 2 × 2 factorial design for comparing cultural effects. When interaction effects of the 2 × 2 × 2 factorial design were significant, Tukey’s HSD test was performed for multiple comparisons between means using the LSMEANS statement in PROC PLM, using the saved model context from the PROC MIXED analysis.

To evaluate the effect of fungicide, Tukey’s HSD test was performed using the LSMEANS statement in PROC MIXED, comparing the fungicide control treatment (in sawdust mulch with narrow drip line and no gypsum amendment) with the treatment with the same combination of cultural factors, but no fungicide. The model included treatment as a fixed effect and bed as a random effect ($P \leq 0.05$).

Results and Discussion

Efficacy of the fungicides

The plants treated with mefenoxam and fosetyl-Al were larger and produced more shoot and root dry weight than in comparable treatment plots (sawdust mulch, narrow drip lines, and no gypsum amendment) without the fungicides (Table 1). However, the percentage of the roots that were infected by *P. cinnamomi* in December was similar between the treatments during both years of the study. It is likely that there was little residual activity of either fungicide in Dec. 2012, ≈7 months after the fungicides were applied in late May. Mefenoxam has a half-life of ≤70 d and, unless applied on a regular basis, does not have extended residual activity against *P. cinnamomi* (Benson, 1987). Fosetyl-Al was even less effective than mefenoxam in reducing root rot of azaleas inoculated with *P. cinnamomi*, leading Benson (1987) to conclude that fosetyl-Al had limited residual activity. Therefore, a better time to capture differences in root infection between the fungicide treatment and the cultural treatments would be within a month or two after fungicide application, when residual activity of each fungicide would have been greater.

Response to the cultural practices

Shoot and root dry weights. Among the cultural treatments, shoot and root dry weight were similar with sawdust and weed mat, but both were affected by drip line placement and the combination of gypsum and drip line placement each year (Table 2). Specifically, plants produced more shoot dry weight and less root dry weight with narrow drip lines than with wide drip lines in year 1. Vargas (2015) also examined the effects of drip line placement in northern highbush blueberry in the absence of *Phytophthora* and found that plant growth was generally greater when the drip lines were placed near the crown than at 20 cm on each side of the row during the first year after planting. The plants in the present study also had less root dry weight with narrow drip lines in year 2, but at this point, had the greatest shoot dry weight when they were treated with a combination of gypsum and wide drip lines.

Root infection. As predicted, the plants had more root infection with weed mat than with sawdust mulch, but only in June or July each year (Fig. 1A), or in Dec. 2013 in plots with weed mat and no gypsum (data not shown). Weed mat generally increased soil temperature relative to sawdust and resulted in more hyphal growth by the pathogen throughout the season (Table 3). Thus, it was somewhat surprising that plant growth was similar between the sawdust and weed mat treatments, as mentioned previously. *Phytophthora cinnamomi* is considered a warm-weather pathogen with optimal growth occurring at 24–28 °C (Erwin and Ribeiro, 1996). Our observations were reflective of this temperature dependence in which hyphal growth was four to five times greater in Aug.

Table 5. Effects of mulch type, drip line placement, and gypsum amendment on soil pH and extractable cations in a field of ‘Draper’ blueberry infested by *Phytophthora cinnamomi* in Corvallis, OR.^z

Treatment	Soil pH		Soil Ca (meq/100 g)		Soil K (meq/100 g)		Soil Mg (meq/100 g)	
	2012	2013	2012	2013	2012	2013	2012	2013
Mulch (M)								
Sawdust	4.6	5.1	15.9	12.2	0.52	0.44	5.0	5.9
Weed mat	4.7	5.3	16.6	12.2	0.48	0.45	5.2	6.1
Significance	NS	NS	NS	NS	NS	NS	NS	NS
Drip lines (D)								
Narrow	4.1 b ^y	4.1 b	4.9	10.8	0.47	0.36 b	4.9	5.8
Wide	5.1 a	5.2 a	5.5	13.5	0.53	0.52 a	5.4	6.2
Significance	M × D*		***	***	***	M × D*	*	*
Gypsum (G)								
No	4.1 c	5.3 a	5.4	10.1 c ^y	0.50	0.46	5.6	6.4
Yes	4.1 c	5.0 b	5.1	11.6 b	0.50	0.43	4.7	5.6
Significance	D × G***		***	D × G**	NS	NS	***	***
Recommended range ^x	4.5–5.5		N/A		>0.38		N/A	

N/A = not available.

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

^zMeasurements were taken at a soil depth of 0–15 cm.

^yMeans followed by the same letter are not significantly different ($P \leq 0.05$).

^xFrom Hart et al. (2006).

Fig. 2. Effects of the interaction between drip line placement and gypsum amendment on Ca²⁺ concentration in the soil solution at (A) 5 months (Oct. 2012) and (B) 16 months (Sept. 2013) after the treatments were initiated in a field of ‘Draper’ blueberry infested by *Phytophthora cinnamomi* in Corvallis, OR. Means with the same letter are not significantly different at each sampling date ($P \leq 0.05$).

2012 and July 2013 than in Apr. 2013 (Table 3). Based on readings at the AgriMet weather station, average maximum soil temperatures at 10- to 20-cm depth (without mulch) were consistently ≥ 24 °C during June through September. Thus, the most likely time of year to observe differences between the two mulch types would be during the summer (Fig. 1A; Table 3), when soil temperatures would reach the optimal hyphal growth temperature more often and for longer periods under weed mat than under sawdust. During the rest of the year, soil temperatures are usually less than the optimal temperature for hyphal growth and frequently drop below the minimum growth threshold of 5–6 °C. Our data show that root infection incidence was similar under sawdust and weed mat during the cooler months (Fig. 1A).

The plants also had more root infection at times with narrow drip lines than with wide drip lines (Fig. 1B), but less infection with gypsum, particularly during the latter months of the season each year (Fig. 1C). Soil water content was greater with the narrow drip lines (Table 4) and, regardless of mulch type or gypsum application, likely increased the activity of the pathogen (de Silva et al.,

1999). Similar results were found in a previous study on ‘Duke’ blueberry at this site (Bryla, 2006). Calcium ions from the gypsum, in contrast to increased water content, likely inhibited the pathogen (Byrt et al., 1982; von Broembsen and Deacon, 1997).

Soil pH and extractable cations. Soil pH and extractable cations were largely unaffected by mulch type each year, but each was often greater near plants with wide drip lines than those with narrow drip lines (Table 5). In general, soil pH decreased after planting, which was likely due to nitrification of NH₄-N from the fertilizers (Bryla and Strik, 2015). Only a fraction of the NH₄-N applied to a field of blueberry is taken up by the plants; the remainder is converted to NO₃-N via nitrification by soil bacteria (Bañados et al., 2012). The process results in the release of H⁺ ions, thereby increasing soil acidity. Presumably, NH₄-N was more concentrated near plants with narrow drip lines, thus reducing pH to a greater extent than with wide drip lines.

The addition of gypsum increased the concentration of extractable Ca in both the soil and the soil solution each year (Table 5; Fig. 2). In both cases, Ca levels decreased over time and, by the second or third year,

were only greater when gypsum was applied in combination with wide drip lines. Apparently, Ca²⁺ ions, which move primarily by mass flow in the soil (Barber, 1995), were more concentrated beneath the plants with wide drip lines and, over time, leached below the root zone. Most of the roots were located <0.3-m deep in each plot (data not shown), which is typical for blueberry (Bryla and Strik, 2007).

With the exception of plots with narrow drip lines in the first year, gypsum reduced soil pH by 0.3 units (Table 5). Usually, gypsum application has little effect on soil pH in nonsodic soils (Shainberg et al., 1989). However, others have reported a slight decrease in the pH of acidic soils after application of gypsum, which was attributed to the salt effect of the Ca²⁺ exchanging H⁺ and Al³⁺ ions from soil colloids into the soil solution (O’Brien and Sumner, 1988; Takahashi et al., 2006; Toma et al., 1999).

Gypsum also reduced the amount of extractable Mg by nearly 1 meq/100 g soil each year (Table 5). Likely, Mg was replaced by Ca from the gypsum and consequently leached to lower depths in the soil (Toma et al., 1999). Because this commonly happens, Sumner (1993) suggested applying Mg fertilizer following a gypsum application to maintain adequate levels of Mg in the soil.

Foliar nutrients. The concentration of most of the important nutrients in the leaves, including P, K, Mg, S, and, in all but one case, Ca, was within or above the range recommended for northern highbush blueberry; however, leaf N concentration was often below the range, particularly in treatments with wide drip lines (Table 6). As mentioned, the plants were fertigated initially with NH₄-N source, which moves very slowly in the soil. Because young blueberry plants have small root systems, much of the N that was applied with wide drip lines in the first year probably never reached the roots before it was converted to NO₃-N (Bryla and Strik, 2015). To compensate, the plants would need to be either fertigated with a mobile source of N, such as urea, or fertilized near the crown

Table 6. Effects of mulch type, drip line placement, and gypsum amendment on the concentration of foliar nutrients in 'Draper' blueberry grown for 2 years (2012–13) in a field infested by *Phytophthora cinnamomi* in Corvallis, OR.

Treatment	Foliar N (%)		Foliar P (%)		Foliar K (%)		Foliar Ca (%)		Foliar Mg (%)		Foliar S (%)						
	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013					
Mulch (M)																	
Sawdust	1.35	1.89	0.10	0.10	0.53	0.47	0.55	0.48	0.17	0.19	0.28	0.12					
Weed mat	1.28	1.60	0.09	0.10	0.49	0.52	0.54	0.42	0.17	0.16	0.23	0.11					
Significance	NS	***	*	NS	**	NS	NS	NS	NS	NS	**	NS					
Drip lines (D)			Sawdust	Weed mat			Sawdust	Weed mat		Sawdust	Weed mat						
Narrow	1.69	2.04	0.10 a ^z	0.10 a	0.10	0.48	0.47	0.53 ab	0.56 ab	0.46	0.16 b	0.17 ab	0.19	0.26	0.12		
Wide	0.94	1.45	0.10 a	0.08 b	0.10	0.54	0.53	0.57 a	0.52 b	0.44	0.18 a	0.17 ab	0.17	0.25	0.12		
Significance	***	***	M × D**		NS	***	NS	M × D**		NS	M × D*		NS	NS	NS		
Gypsum (G)		Narrow	Wide				Narrow	Wide		Narrow	Wide		Narrow	Wide			
No	1.30	2.03 a	1.35 c	0.10	0.10	0.46	0.46	0.53 bc	0.50 c	0.38	0.17 b	0.16 b	0.18	0.23 c	0.15 d	0.10	
Yes	1.33	2.05 a	1.56 b	0.10	0.11	0.57	0.53	0.55 ab	0.60 a	0.52	0.17 b	0.19 a	0.18	0.28 b	0.34 a	0.13	
Significance	NS	D × G*		NS	NS	M × D × G*		NS	D × G**		*	D × G***		NS	D × G***		***
Recommended range ^y	1.76–2.00		>0.07		0.41–0.70		0.41–0.80		0.13–0.25		0.11–0.16						

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

²Means followed by the same letter are not significantly different ($P \leq 0.05$).

³Recommendations are from Strik and Vance (2015).

with a granular N product. Liquid urea was indeed more effective in the second year than liquid ammonium sulfate was in the first year, but leaf N continued to remain below the recommended range in the treatments with wide drip lines. Vargas (2015) tried spreading small doses of granular urea around the plants before fertigating with wide drip lines; the treatment resulted in greater leaf N than fertigation only, but it did not improve plant growth. More research is needed to develop a suitable method for providing adequate N with wide drip lines during plant establishment.

By the second year, the concentration of Ca in the leaves was slightly below the recommended range in plants grown in plots without gypsum (Table 6). Apparently, soil Ca was insufficient at the site unless gypsum was applied. Low soil pH can sometimes lead to low leaf Ca concentrations in blueberry (Hart et al., 2006). However, the soil pH was always near or within the desired range in each treatment (Table 5). When foliar Ca is low, Hart et al. (2006) recommend applying 1–2 t ha⁻¹ of lime if the soil pH is <4 and 1–2 t ha⁻¹ of gypsum if the pH is >5. A slightly greater rate of gypsum (2.24 t ha⁻¹) was applied in the present study. Adding gypsum increased the concentration of both Ca and S in the leaves, particularly with wide drip lines in the first year. These ions are mobile in the soil and often become concentrated in the root zone with wide drip lines (Mmolawa and Or, 2000). Leaf Ca and S concentrations were also affected by mulch type in the first year. That year, foliar Ca was greater with sawdust than with weed mat when the plants were irrigated with wide drip lines, whereas leaf S was greater with sawdust than with weed mat regardless of the drip lines.

Mulch type, drip placement, and gypsum also affected the concentration of other nutrients in the leaves during the first growing season (Table 6). Foliar P, for example, was lower with wide drip lines than with narrow drip lines, but only when the plants were mulched with weed mat. Foliar K, on the other hand, was greater with sawdust mulch, wide drip lines, and gypsum, on average, and

the additive combination of each resulted in the highest concentration of foliar K (i.e., 0.66%) among the treatments. Finally, foliar Mg was greater with wide drip lines than with narrow lines under sawdust and was also greater with the combination of wide drip lines and gypsum than with narrow drip lines or no gypsum. Although the cause of the observed treatment effects on foliar P levels is unclear, Vargas (2015) found that K and Mg moved with the wetting front and concentrated near the plants irrigated with wide drip lines.

Conclusions

Based on the results of this study, it appears that gypsum and wide drip lines are effective at suppressing phytophthora root rot in northern highbush blueberry. Together, these practices resulted in the largest plants among the cultural treatments but still did not increase plant growth to levels similar to those obtained with fungicides. However, plant growth was limited during the first year with the treatments, primarily as a result of N deficiency with the wide drip lines. Research is underway to identify a method to correct the problem.

Weed mat increased root infection by *P. cinnamomi* relative to sawdust and resulted in warmer soil conditions and greater hyphal growth. Although plant growth was not adversely affected after 2 years with weed mat, caution is warranted when using weed mat with susceptible cultivars (Yeo et al., 2016) and at sites conducive to phytophthora root rot (e.g., heavy soils and poor drainage).

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