Research

Phoma Leaf Spot Susceptibility and Horticultural Characteristics of Table Beet Cultivars in New York

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Abstract

Phoma leaf spot (PLS), caused by *Phoma betae* (syn. *Neocamarosporium betae*), is an important fungal disease affecting table beet (*Beta vulgaris* L. subsp. *vulgaris*) production in New York. PLS lesions on the foliage can lead to rejection in fresh market sales and can reduce leaf integrity, which can disrupt mechanized harvesting. Eight popular table beet cultivars were assessed for susceptibility to PLS using *P. betae* isolates representative of the New York population in two small-plot, replicated field trials in Geneva and Freeville, NY. There were significant differences in PLS incidence, severity, and epidemic progress (as measured by area under the disease progress stairs) and horticultural characteristics among cultivars. Non-red table beet

cultivars (Avalanche, Boldor, and Chioggia Guardsmark) were less susceptible to PLS than red cultivars (Falcon, Merlin, Rhonda, Red Ace, and Ruby Queen). Significant differences in fresh weight of roots and dry weight of foliage were detected between cultivars at harvest (86 days after planting [DAP] in Freeville and 91 DAP in Geneva). Falcon had significantly higher root weight than Boldor, and Ruby Queen produced significantly more foliage than Boldor. Information on the performance of these cultivars provides locally valuable information for cultivar selection in a broad range of markets.

Keywords: cultural practices, vegetables, fungal disease

New York (NY) is currently the second largest producer of table beet (*Beta vulgaris* L. subsp. *vulgaris*) in the United States, representing 26% of that grown in 2012 (USDA-NASS 2012). Recently, there has been an expansion in table beet production owing to an increased awareness by consumers of the potential health benefits of consumption (Clifford et al. 2017; Navazio et al. 2010; Pethybridge et al. 2018). Table beets are grown in NY for processing into cans and jars, fresh market sales of roots and/or foliage, and use in value-added products such as juices and powders (Pethybridge et al. 2018). For processing, root size, shape, texture, uniformity, flavor, color, and quality are important cultivar characteristics (Goldman and Navazio 2003; Kikkert et al. 2010; Pethybridge et al. 2018; USDA 2017). Root and foliage characteristics are also important for fresh market sales yet can be more diverse in color and appearance to appeal to a broader consumer base.

Disease management is critical to ensuring profitability and productivity of table beet production (Abawi et al. 1986; Kikkert

et al. 2010; Pethybridge et al. 2018; Shah and Stivers-Young 2004). One of the most important foliar diseases is Phoma leaf spot (PLS), caused by the fungus, *Phoma betae* (syn. *Neocamarosporium betae*) (Ariyawansa et al. 2015), which can cause loss of green leaf area, deleteriously affecting root yield and quality (Pool and McKay 1915). On foliage, PLS symptoms are tan-brown lesions with light brown centers and dark concentric rings (Fig. 1) (Harveson et al. 2009; Pool and McKay 1915). At crop emergence, *P. betae* can cause pre- and post-emergence damping-off, which can negatively affect crop stands (Edson 1915; Pethybridge et al. 2018). On roots, *P. betae* can cause Phoma root rot, which manifests as dry, black necrotic lesions usually beginning at the crown (Harveson et al. 2009). Latent infection of roots can lead to substantial losses from decay in storage (Bugbee 1982; Pethybridge et al. 2018). In NY, surveys detected PLS in 35 of 60 table beet fields in 2017 and 2018. Moreover, the prevalence of PLS was higher in fields grown using organic production practices (74%) than conventional techniques (49%) (Koenick and Pethybridge, *unpublished data*).

P. betae is commonly introduced to fields through infected seed (Edson 1915; Herr 1971; Leach and MacDonald 1976; Mangan 1971) and can overwinter in soil on plant debris for up to 26 months (Bugbee and Soine 1974). During the cropping season, *P. betae* undergoes asexual reproduction, producing pycnidia, and the resulting conidia can be dispersed short distances via water splash (Harveson et al. 2009; Monte and García-Acha 1988). Although the sexual form has not been observed in NY (Pethybridge, *unpublished data*), *P. betae* is capable of sexual reproduction, producing pseudothecia and ascospores that can be disseminated long distances via wind (Bugbee 1979). Koenick et al. (2019) found

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P. betae to be heterothallic and molecular evidence for NY populations of *P. betae* to use a mixed reproductive mode throughout the growing season. Genetic differentiation and population structure among NY populations and those from Washington state supported within-field and external inoculum sources to influence PLS epidemics (Koenick et al. 2019). Quantifying the temporal progression of a disease can also enhance our understanding of the relative importance of different inoculum sources and the various options, such as cultivar susceptibility, for improving disease management strategies (Jeger 2004; Madden et al. 2007; Vanderplank 1963).

Disease management in conventional table beet production is often reliant upon multiple applications of fungicides (Pethybridge et al. 2018; Vaghefi et al. 2016). If best management guidelines are not used, reliance on fungicides may not be sustainable owing to the potential for development of resistance to those with single-site modes of action (Brent and Hollomon 2007). For organic table beet production, the inability to use conventional fungicides makes cultural strategies, such as crop rotation, field design manipulation, and cultivar selection, critical for effective disease management (Shah and Stivers-Young 2004). These strategies are also beneficial to ensure horticultural characteristics, such as root size and shape,

FIGURE 1

Phoma leaf spot symptoms caused by *Phoma betae* on different table beet cultivars within two replicated field trials conducted in New York in 2018: **A**, Rhonda; **B**, Red Ace; **C**, Merlin; **D**, Falcon; **E**, Chioggia Guardsmark; **F**, Avalanche; **G**, Boldor; and **H**, Ruby Queen.

meet market requirements (Clark et al. 1967; Kikkert et al. 2010). The processing industry dictates acceptable table beet root size and shape to enable fit into cans and jars (USDA 2017), resulting in the use of only a few cultivars. For the fresh market, there is more flexibility in cultivar selection, and hence there is potential to select cultivars that are less susceptible to disease. Variations in the susceptibility of selected table beet cultivars have been quantified for *Cercospora* leaf spot caused by *Cercospora beticola* (Pethybridge et al. 2017a) and other diseases of sugar beet (Smith and Martin 1978). In organic production systems, the selection of cultivars with enhanced disease resistance may also reduce the use of copper, lessening build-up in soil and the potential for plant damage from phytotoxicity resulting from interactions at high temperatures (Pethybridge et al. 2017a, 2017b). To the best of our knowledge, no information on the susceptibility of table beet cultivars to PLS is available. The objectives of this study were to evaluate PLS susceptibility of popular table beet cultivars and characterize important horticultural characteristics under NY growing conditions.

Field Trial Design and Weather

The susceptibility of eight table beet cultivars (Avalanche, Boldor, Chioggia Guardsmark, Falcon, Merlin, Rhonda, Red Ace, and Ruby Queen) to infection by *P. betae* was assessed in two small-plot, replicated field trials in 2018. Cultivars were selected based on popularity of use in NY small, mixed-vegetable farms and to encompass a broad range of end uses and root characteristics (Table 1). Commercial seed lots were used; seed companies and treatments are listed in Table 1. Notably, Boldor seeds were untreated, Rhonda seeds had a proprietary organic film coat, and seeds of other cultivars were fungicide treated.

The location of one field trial was at the Homer C. Thompson Research Farm (Freeville, NY; 42.52°N, 76.34°W), and the second trial was at the Research North Farm of Cornell AgriTech at The New York State Agricultural Experiment Station (Geneva, NY; 42.87°N, 77.03°W). The soil type at Freeville was a Howard gravel loam. The soil type at Geneva was a Lima silt loam.

Each trial was planted using an identical randomized block design, and each cultivar was replicated five times. In Freeville, a plot consisted of four rows (38 cm between individual rows and 4.6 m long). There were four unplanted buffer rows between plots and a ~1.5-m unplanted alley between plots within rows, which

were cultivated for weed control as needed. In Geneva, a plot consisted of two rows (76.2 cm between individual rows), each 4.6 m long. Two buffer rows of Ruby Queen separated plots among rows, and there was a ~1.5-m unplanted alley between plots within rows.

The trial at Freeville was planted on June 12, 2018, with a Monosem vacuum planter (Monosem, Edwardsville, KS) at an in-row planting density of 56.1 seeds/m. The trial at Geneva was planted on June 21, 2018, with a Jang JP1 clean seeder (Jang Automation, Cheongju, South Korea) at an in-row plant density of 30.4 seeds/m. In Freeville, 560.43 kg/ha of 20N-10P-10K fertilizer (Phelps Supply, Phelps, NY) was broadcast applied and shallow incorporated prior to planting and S-metolachlor herbicide (Dual Magnum, Syngenta Corp., Greensboro, NC) applied at 0.78 liter/ha on the same day as planting. At 51 days after planting (DAP), an application of spinosad insecticide (0.58 liter/ha; Entrust SC, Dow AgroSciences, Indianapolis, IN) with an adjuvant (0.04% v/v; Induce, Helena Agri-Enterprises, Collierville, TN) was made for leaf miner control. Ammonium nitrate (22.7 kg/ha; Phelps Supply) was side dressed by hand at 49 DAP.

In Geneva, 10N-5P-10K plus boron at 2.2 kg/ha (Phelps Supply) was broadcast at 336.26 kg/ha prior to planting and banded at 392.3 kg/ha during planting. The herbicide S-metolachlor (0.78 liter/ha) was applied on the same day as planting. Both trials were irrigated as needed to maintain optimal plant growth and disease development.

Weather. On-site average monthly temperature and precipitation data for both field locations were obtained from the Northeast Regional Climate Center (<http://climod2.nrccl.cornell.edu/>). Data at each location were compared with the long-term averages (LTA) (1981 to 2010) (Northeast Regional Climate Center 2018). Growing degree days (GDD₁₀) calculated with a base of 10°C were also obtained from the Northeast Regional Climate Center and compared with the LTA.

Weather during the growing seasons in Geneva and Freeville was similar to the LTA. At Geneva, the average minimum and maximum temperatures were 12.9 and 23.5°C (June), 16.7 and 27.8°C (July), 17.4 and 26.1°C (August), and 13.2 and 22.8°C (September). At Freeville, the average minimum and maximum temperatures were 11.3 and 23.2°C (June), 15.2 and 27.8°C (July), 16.6 and 25.9°C (August), and 12.9 and 22.8°C (September). Temperatures were less than 10% different than the LTA in both locations, with

TABLE 1
Characteristics of cultivars evaluated for susceptibility to Phoma leaf spot caused by *Phoma betae* in replicated field trials in New York in 2018

Cultivar	Color	Root shape	Primary use ^w	Time to maturity (days) ^x	Seed company ^y (city, state)	Seed treatment ^z
Avalanche	White	Globe	FM	55	Harris Seeds (Rochester, NY)	M, T, F
Boldor	Yellow	Globe	FM	55	Johnny's Seeds (Fairfield, ME)	Untreated
Chioggia	Pink and	Globe	FM	55	Sakata (Morgan Hill, CA)	M, T, F
Guardsmark	white striped					
Falcon	Red	Blocky	FM	80–85	Sakata (Morgan Hill, CA)	M, T
Merlin	Red	Globe	FM	48	Harris Seeds (Rochester, NY)	M, T
Red Ace	Red	Globe	P and FM	50	Harris Seeds (Rochester, NY)	M, T
Rhonda	Red	Globe	FM	65–70	Bejo (Geneva, NY)	Organic treatment
Ruby Queen	Red	Globe	P	55	Seneca Foods (Geneva, NY)	T

^w FM = fresh market, and P = processing.

^x From direct seeding to harvest.

^y Company is where seeds were obtained and are not necessarily the breeder of the cultivar.

^z M = mefenoxam; T = thiram; and F = fludioxonil.

the only exceptions being minimum temperatures in August and September. In both locations, August and September minimum temperatures were up to 12% higher compared with the LTA. The average monthly rainfall was 6.9 cm (June), 8.1 cm (July), 17 cm (August), and 8.7 cm (September) at Geneva; and 4.9 cm (June), 17.7 cm (July), 11.3 cm (August), and 13.1 cm (September) at Freeville. The cropping season was wetter with a 14 and 15% increase in total precipitation for June through September compared with the LTA in Geneva and Freeville, respectively. A total of 2,246 GDD₁₀ accumulated during the growing season in Geneva (LTA = 2,052) and 2,111 GDD₁₀ accumulated in Freeville (LTA = 1,880).

Preparation and application of *P. betae* inoculum. The entire trial area was inoculated at 42 DAP (Geneva) and 56 DAP (Freeville), when plants had 10 to 15 true leaves. *P. betae* isolates collected in NY from diseased table beet leaves (RN1, RN20, TR1, and TR30) were used to prepare conidial inoculum. No information is available on differences in virulence and aggressiveness among *P. betae* isolates in the NY population. However, the high genetic diversity typically observed in *P. betae* populations suggests that differences in virulence may be likely (Koenick et al. 2019), and hence a mixed inoculum of representative isolates was preferred for these trials.

Inoculum was prepared by removing the isolates from long-term storage (−20°C) and subculturing onto clarified V8 (CV8) juice (10% [v/v] CV8 juice [Campbell's Soup Co., Camden, NJ], 0.5% [w/v] CaCO₃ agar (Jeffers 2015; Miller 1955). After 5 to 7 days of growth, each plate was subcultured onto four new CV8 plates and incubated for 14 days in a 12-h photoperiod at room temperature to induce sporulation. Sterile distilled water (5 ml) was added to each plate, and a scalpel was used to dislodge pycnidia into a falcon tube with 20 ml of sterile distilled water. The falcon tube was vigorously vortexed, and the solution was passed through two layers of sterile muslin cloth into a new suspension. A hemocytometer was used to quantify conidial concentration in the resulting suspension. The concentration of the inoculum was 7×10^4 conidia/ml (Geneva) and 4×10^4 conidia/ml (Freeville) with 0.1% (v/v) polysorbate 20 (Tween-20, Agdia, Elkhart, IN) added before application. To quantify germination efficiency, 100 µl of the suspension was spread over the surface of three 2% water agar (Difco Agar, Becton, Dickinson and Company, Sparks, MD) plates. After 24 h, the germination of 100 arbitrarily selected conidia was evaluated at 63× magnification (Olympus SZX10 Zoom Stereo Microscope, Olympus, Tokyo, Japan). A conidium was considered germinated if the germ tube was at least twice the length of the conidium. Germination efficiency of the conidia was 98 and 97% for the Geneva and Freeville trials, respectively.

For each trial, 6 liters of inoculum (+ 0.1% v/v polysorbate 20) was applied within 5 h of preparation. The inoculum was applied with a backpack sprayer (DB Sprayer Professional, Fountainhead Group, New York Mills, NY) at a rate of 8.2 ml/m with a walking speed of 1.67 s/m.

Evaluating for disease and yield characteristics. In-row plant density counts (number of plants/m) were conducted at 28 DAP at both locations following stabilization of plant stands. PLS incidence and severity were assessed on 10 arbitrarily selected leaves from each of two rows (20 leaves per plot) and averaged on a per plot basis. Incidence was defined as the number of leaves with at least one PLS lesion divided by 20 leaves multiplied by 100. Severity was defined as the percentage of symptomatic area relative to total leaf area and averaged per plot. In Freeville, leaves were only selected from the middle two rows of each plot. Disease assessments were conducted at least six times throughout the growing season. In Freeville, assessments were made at 0 (August 3), 8 (August 15), 12 (August 19), 15 (August 22), 22 (August 29), and

28 (September 5) days postinoculation (DPI). In Geneva, assessments were made at 0 (August 2), 8 (August 8), 13 (August 15), 16 (August 18), 20 (August 22), 26 (August 28), 32 (September 4), 39 (September 11), and 46 (September 18) DPI. Disease assessments were recorded on a tablet using the Android application Field Book (Rife and Poland 2014).

Trials were harvested by hand at 86 DAP (Freeville) and 91 DAP (Geneva). Plants were removed from two 0.5-m transects within each plot and separated into foliage and roots. The fresh weight of foliage (kg) was recorded in the field. A subsample of the foliage was weighed and dried at 37.5°C for 4 days to calculate percent dry matter. The roots from each plot were counted and weighed (kg). A subsample of up to 20 roots was randomly selected from each plot for measurement of root diameter (mm) with electronic calipers. When less than 20 roots were harvested from each plot, the shoulder diameter of all roots was measured.

Data Analysis

All statistical analyses were performed in R statistical software version 3.5.1 (R Core Team 2017). Disease severity at each evaluation was used to calculate the area under the disease progress stairs (AUDPS) as a measure of epidemic progression (Simko and Piepho 2012). First, the area under the disease progress curve (AUDPC) was calculated in the R package *agricolae* version 1.2-8 (De Mendiburu 2017), and then it was converted to AUDPS using the following formula (Simko and Piepho 2012):

$$\text{AUDPS} = \text{AUDPC} + \left(\frac{y_1 + y_n}{2} \times \frac{D}{n-1} \right) \quad (1)$$

Effect of cultivar. The R package *lme4* version 1.18 (Bates et al. 2015) was used to create mixed models with table beet cultivar as a fixed effect and replication as a random effect. The effect of cultivar on PLS incidence, severity, and AUDPS was evaluated through analysis of variance (ANOVA). To check assumptions of normality and homoscedasticity, quantile-quantile plots (Atkinson 1987), histograms with a normality curve overlaid, and residual plots were evaluated visually in the R packages *car* version 3.0-2 (Fox and Weisberg 2011), *rcompanion* version 2.0.0 (Mangiafico 2018), and *ggplot2* version 3.1.0 (Wickham 2016), respectively. When necessary, the Shapiro–Wilk test (Shapiro and Wilk 1965) was conducted in the R package *stats* version 3.6.0 (R Core Team 2017) as another formal test of normality. Outliers were checked with Cook's distance (Cook and Weisberg 1982) in *stats*. Transformations were made as needed. Data for root number in the Geneva field trial benefited from a log transformation, and AUDPS (Freeville field trial) required a square-root transformation to remove skew and comply with ANOVA assumptions.

The effect of plant density as a covariate on disease and yield component response variables was assessed using ANOVA and included in models when significant ($P < 0.05$). Significant differences ($P = 0.05$) in the means between cultivars in each trial were identified using the Tukey–Kramer honestly significant difference method (Miller 1981) in the R package *emmeans* version 1.3.0 (Lenth et al. 2018). Data for each field trial were analyzed separately.

Temporal disease progress. Temporal analysis of epidemics was conducted using PROC REG (SAS version 9.4, SAS Institute, Cary, NC). Disease progression was fit to exponential, monomolecular, logistic, and Gompertz models for each field trial. Disease epidemics may be classified as monocyclic (one infection cycle per crop cycle) or polycyclic (multiple infection cycles per crop cycle)

(Madden et al. 2007; Vanderplank 1963). A monomolecular model is usually the best fit of a monocyclic epidemic, whereas Gompertz and logistic models are usually the best descriptors of a polycyclic epidemic (Madden et al. 2007). Goodness of each model fit was determined by examining residual plots for normality, randomness, and constant variance and by viewing the following fitness statistics for linearity: *F* statistic, coefficient of determination (R^2), the root mean square error (RMSE), and coefficient of variation (CV). Comparisons between models were conducted by calculating the back-transformed fitted (R^{*2}) severity values of the original. Within each cultivar, fit of the selected model was summarized using the R^{*2} , RMSE, CV, and slope and intercept values.

Cultivar Susceptibility to PLS

Symptoms of PLS were typical tan-brown lesions with dark concentric rings of pycnidia and similar across table beet cultivars (Fig. 1). Significant differences in PLS susceptibility and horticultural characteristics were observed among cultivars at both locations. Cultivar had a significant effect on in-row plant density at both locations (Table 2) and was a significant covariate for root diameter and average root weight at Geneva but did not influence response variables at Freeville.

Differences in PLS incidence, severity, and progression were also observed among cultivars. Non-red cultivars had significantly lower PLS incidence than red cultivars (Table 2). At Geneva, on average, PLS incidence was 47.3 and 86% in non-red and red cultivars, respectively, at the final assessment. In Freeville, PLS incidence was lowest in Chioggia Guardsmark and Boldor with an average of 29.5%. PLS incidence was significantly higher in red than non-red cultivars with an average of 77.2% (Table 2).

At the final assessment, PLS severity was lowest in Chioggia Guardsmark in both trials (7.9 and 5% in Geneva and Freeville, respectively). In contrast, PLS severity was highest in Rhonda in both trials and was significantly different from all cultivars except Falcon at Geneva. PLS severity in Rhonda was 342 and 862% higher than in Chioggia Guardsmark at Geneva and Freeville, respectively. Of the red cultivars, final PLS severity was not significantly different between Red Ace, Falcon, Merlin, and Ruby

Queen in both trials (Table 2). PLS severity in Red Ace was 48.5 and 123.7% less than in Rhonda at Geneva and Freeville, respectively. Similar trends in PLS susceptibility were observed among non-red and red cultivars when evaluating AUDPS (Fig. 2; Table 2). AUDPS was significantly lower in non-red cultivars than red cultivars at Geneva. Chioggia Guardsmark and Boldor had the lowest AUDPS values at Freeville, and AUDPS values were not significantly different among Falcon, Merlin, Red Ace, and Ruby Queen in both trials (Table 2). Rhonda had the highest AUDPS values in both trials. Temporal disease progress in Rhonda and Falcon was best fit to a Gompertz model (Table 3).

Horticultural Characteristics of Cultivars

Significant differences were found among cultivars for all root characteristics at Geneva (Table 4). Ruby Queen produced significantly more roots than other cultivars. Of the red cultivars, Ruby Queen produced 151, 153, 259, and 230% more roots than Falcon, Merlin, Red Ace, and Rhonda, respectively. Root number was not significantly different between Avalanche, Boldor, Red Ace, and Rhonda (Table 4). At Geneva, Ruby Queen and Chioggia Guardsmark produced smaller roots. Root diameter was not significantly different between Avalanche, Boldor, Falcon, Red Ace, and Rhonda, but these were significantly larger than Ruby Queen. Root weight was significantly higher in Falcon than Ruby Queen at Geneva and than Boldor at both locations. For example, Falcon produced 100 and 107% more root biomass than Boldor at Geneva and Freeville, respectively. There were no significant differences in root number, root diameter, and average root weight among cultivars at Freeville (Table 4).

Cultivar also had a significant effect on the dry weight of foliage in both trials (Table 4). For example, Boldor produced significantly less foliage than Chioggia Guardsmark and Ruby Queen. At Freeville, Boldor produced significantly less foliage than other cultivars except for Rhonda. The dry weight of foliage was not significantly different between Chioggia Guardsmark, Falcon, Merlin, Red Ace, Rhonda, and Ruby Queen at Freeville and between Avalanche, Chioggia Guardsmark, Falcon, Merlin, Rhonda, and Ruby Queen at Geneva (Table 4).

TABLE 2
Effect of table beet cultivar on plant density and the incidence and severity of *Phoma* leaf spot (PLS) caused by *Phoma betae* at harvest, and epidemic progress in two field trials at Geneva and Freeville, NY, in 2018

Cultivar	Plant density ^w		Incidence (%) ^x		Disease severity (%) ^x		AUDPS ^y	
	Geneva	Freeville	Geneva	Freeville	Geneva	Freeville	Geneva	Freeville
Avalanche	13.9 ab ^z	27.5 ab	56 a	48 b	15.3 b	14.6 ab	352.7 b	15.2 (233.3) b
Boldor	8.5 a	14.7 a	42 a	28 a	10.9 ab	5.2 a	264.6 ab	7.7 (60.0) a
Chioggia Guardsmark	21.9 c	35.3 b	44 a	31 a	7.9 a	5.0 a	168.7 a	8.7 (76.9) a
Falcon	17.5 bc	25.9 ab	87 b	78 cd	29.2 cd	30.7 c	560.2 c	20.9 (445.3) c
Merlin	16.3 bc	21.1 ab	87 b	76 cd	27.0 c	30.1 c	599.5 c	20.7 (427.8) c
Red Ace	12.2 ab	18.4 a	82 b	65 c	23.5 c	21.6 bc	554.1 c	17.8 (318.4) bc
Rhonda	14.6 ab	17 a	90 b	88 d	34.9 d	48.1 d	786.1 d	27.0 (732.4) d
Ruby Queen	39.4 d	29.9 ab	84 b	79 cd	26.9 c	27.8 c	613.4 c	19.3 (375.4) c
HSD	7.3	16.3	16	15	7.11	10.61	139.52	3.58
<i>F</i>	41.54	4.65	37.96	56.90	41.65	45.66	49.07	74.48
<i>P</i>	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

^w In-row plant density counts (number of plants/m) evaluated at 28 days after planting.

^x Incidence is the number of leaves with at least one PLS lesion/total number of leaves × 100; severity is the percentage of the leaf affected by PLS relative to the total leaf area.

^y Area under the disease progress stairs (Simko and Piepho 2012); nontransformed values are in parentheses.

^z Values given are the means of five replicates. Means followed by the same letter in a column are not statistically different using the Tukey–Kramer honestly significant difference (HSD) ($P \leq 0.05$).

Study Implications and Conclusions

Maintaining foliar health is essential for profitable table beet production to minimize crop losses through facilitation of mechanized harvest and ensuring high product quality for direct sales (Pethybridge et al. 2018). Strict quality standards make selection of

cultivars with varying susceptibility to PLS and other diseases an important tool for disease management. To the best of our knowledge, this is the first study to evaluate the susceptibility of eight popular table beet cultivars to PLS, and results were consistent across trials. Minor differences in disease severity and epidemic

FIGURE 2

Disease progress curves depicting Phoma leaf spot epidemics caused by *Phoma betae* for non-red and red table beet cultivars at field trials in New York in 2018: **A**, non-red, Geneva; **B**, red, Geneva; **C**, non-red, Freeville; and **D**, red, Freeville. AV = Avalanche; BO = Boldor; CG = Chioggia Guardsmark; FA = Falcon; ML = Merlin; RA = Red Ace; RH = Rhonda; and RQ = Ruby Queen.

progress between trials may be explained by variation in environmental conditions, plant age, and agronomic factors. However, temperature and rainfall totals and patterns over the cropping season were similar between the locations and the LTA. Some damage from site-specific biotic stresses was incurred and was homogeneous over the trial areas. For example, moderate damage from leaf miner was incurred at Freeville and required an insecticide application.

Owing to machinery differences, row spacing within plots at Freeville was half of that at Geneva. Row spacing can affect final yields, root size, and disease incidence (Kikkert et al. 2010; Shah and Stivers-Young 2004). A survey conducted between 1998 and 2000 found that narrower row spacing increased the incidence of root decay in table beets (Shah and Stivers-Young 2004). Moreover, in general, positive correlations between plant density and disease incidence have been well characterized across many pathosystems (Burdon and Chilvers 1982). Trade-offs between yield components and disease are important to quantify because they may form an integral part of a durable management strategy for foliar disease in table beet.

Higher PLS severity across cultivars at Freeville compared with Geneva could also be attributed to differences in growth stage. Plants were 2 weeks older in Freeville when inoculated than at Geneva. Age has been reported as a factor in the susceptibility of sugar beet to PLS, with older leaves being more susceptible (Pool

and McKay 1915). Despite differences in field design and plant age, differences between cultivars in PLS susceptibility were similar among field trials.

In both field trials, non-red cultivars (Avalanche, Boldor, and Chioggia Guardsmark) were less susceptible to PLS than red cultivars (Red Ace, Ruby Queen, Merlin, Rhonda, and Falcon). Betalains, a class of alkaloid pigments, are responsible for color variation in table beet (Goldman and Navazio 2008). Betalains include red-violet betacyanin and yellow betaxanthin pigments, and they convey multiple advantages for plant growth and defense (Georgiev et al. 2008). For example, betalains have been reported as important for attracting pollinators and animals for seed dispersal and for mitigating abiotic stress (Georgiev et al. 2008; Polturak and Aharoni 2018; Stintzing and Carle 2004). The function of betalains in response to biotic stress is less described; however, the few studies available describe betalain production to be beneficial for defense against fungal and bacterial pathogens (Polturak and Aharoni 2018). Tobacco plants producing red betalain pigments exhibited increased resistance toward the gray mold pathogen, *Botrytis cinerea* (Polturak et al. 2017), and it has been suggested that betalains evolved in plants for their antifungal properties (Brockington et al. 2011). Further studies are warranted to elucidate the genetic basis of resistance and any associations with betalain production in response to specific pathogens, such as *P. betae*.

TABLE 3
Disease progression of Phoma leaf spot epidemics caused by *Phoma betae* in table beet cultivars Rhonda and Falcon at Freeville and Geneva, NY, in 2018

Cultivar, field	Best fit ^w	Slope	Intercept	R ² ^x	RMSE ^y	F statistic	P	CV (%) ^z
Rhonda, Geneva	Gompertz	0.041	-1.78	0.92	0.18	65.85	0.0002	-23.71
Rhonda, Freeville	Gompertz	0.075	-1.64	0.96	0.19	45.61	0.0066	-48.36
Falcon, Geneva	Gompertz	0.041	-2.0	0.97	0.11	162.53	<0.0001	-11.83
Falcon, Freeville	Gompertz	0.072	-1.99	0.89	37.95	15.82	0.0284	-37.95

^w Best fit from comparisons between the exponential, monomolecular, logistic, and Gompertz models.

^x Back-transformed R².

^y Root mean square error.

^z Coefficient of variation.

TABLE 4
Horticultural characteristics of table beet cultivars at harvest in two field trials inoculated with *Phoma betae* in Geneva and Freeville, NY, in 2018^y

Cultivar	No. roots/m		Root diameter (mm)		Fresh root weight (kg/m)		Average root weight (g)		Dry foliage weight (g)	
	Geneva	Freeville	Geneva	Freeville	Geneva	Freeville	Geneva	Freeville	Geneva	Freeville
Avalanche	2.7 (15.6) a ^z	33.3 a	69.1 cd	35.7 a	3.7 bc	1.3 abc	245.4 cd	41.2 a	165.2 ab	197.1 c
Boldor	2.5 (12) a	20.1 a	66.9 cd	39.8 a	2.2 a	0.9 a	187.1 bc	54.6 a	101.0 a	67.6 a
Chioggia Guardsmark	3.4 (30.6) bc	24.1 a	53.9 ab	36.2 a	2.9 ab	1.0 ab	97.9 ab	41.2 a	196.5 b	152.4 bc
Falcon	2.9 (19.8) ab	27.7 a	64.6 bcd	42.7 a	4.4 c	1.8 c	229.4 cd	64.2 a	157.6 ab	128.0 b
Merlin	3.0 (19.6) ab	28.9 a	60.8 bc	41.8 a	3.4 bc	1.4 abc	183.9 bc	55.3 a	151.6 ab	133.8 b
Red Ace	2.6 (13.8) a	30.4 a	73.1 d	40.0 a	4.0 bc	1.2 ab	305.0 d	44.3 a	109.7 a	130.8 b
Rhonda	2.7 (15.8) a	33.9 a	71.3 cd	41.0 a	3.9 bc	1.5 bc	269.4 cd	51.3 a	136.1 ab	98.8 ab
Ruby Queen	3.9 (49.6) c	30.3 a	47.2 a	38.0 a	2.9 ab	1.5 bc	60.2 a	47.5 a	197.1 b	133.5 b
HSD	0.53	17.19	12.16	10.97	1.21	0.56	108.07	33.85	80.95	57.96
F	18.3	1.56	2.76	0.79	7.64	5.99	5.22	1.19	4.52	9.31
P	<0.001	0.190	0.026	0.600	<0.001	<0.001	<0.001	0.341	0.002	<0.001

^y Trials were harvested at 91 and 86 days after planting in Geneva and Freeville, respectively. Nontransformed values in parentheses.

^z Values given are the means of five replicates harvested from a 1-m transect in each plot. Means followed by the same letter in a column are not statistically different using the Tukey–Kramer honestly significant difference (HSD) ($P \leq 0.05$).

Temporal progress of PLS epidemics in Rhonda and Falcon were best fit to a Gompertz model, suggestive of a polycyclic disease. Similar temporal patterns have been depicted for comparable pathosystems including ray blight of pyrethrum caused by *Phoma ligulicola* (syn. *Stagonosporopsis tanacetii*) (Pethybridge et al. 2005) and disease caused by *Corynespora cassiicola* on cotton (Bowen et al. 2018). Foundational knowledge of the biology of *P. betae* also supports a polycyclic epidemic in table beet (Harveson et al. 2009). Polycyclic diseases can be managed by reducing the rate (dy/dt) of disease progression (Madden et al. 2007). Selection of table beet cultivars that are less susceptible to PLS or other in-season tactics (i.e., fungicides) are important to achieve this goal.

This study demonstrated that in-row plant density significantly differed among cultivars and corroborated its relationship with table beet root characteristics, including diameter and weight. This finding confirms previous studies that higher plant density is positively correlated with root number but negatively correlated with root size and weight (Benjamin and Bell 1985; Kikkert et al. 2010; Mack 1979). At Geneva, Ruby Queen produced the highest number of roots per row meter; however, Ruby Queen also produced smaller roots on average than other cultivars. Most yield components were similar among non-red and red cultivars. In Geneva, root number did not significantly differ between Avalanche (white), Boldor (yellow), Red Ace (red), and Rhonda (red). Additionally, root diameter did not significantly differ between Avalanche (white), Boldor (yellow), Falcon (red), Red Ace (red), and Rhonda (red). In Freeville, there were no significant differences among cultivars in root diameter and individual root weight. Cultivars that were less susceptible to PLS did not necessarily have higher yields. In both trials, there were no significant differences in foliage among six table beet cultivars, including red and non-red representatives. Although Boldor was less susceptible to PLS, root and foliage biomass was significantly lower compared with other cultivars at both locations. Additional research to disentangle relationships between PLS and crop loss is essential to fully understand the effects of this disease on productivity and profitability. Cultivar evaluation in other locations would also be beneficial, because disease susceptibility and horticultural characteristics may vary with microclimate and local pathogen populations.

This study quantified differences among eight table beet cultivars in PLS susceptibility and horticultural characteristics in NY. Non-red cultivars were less susceptible than red cultivars to PLS. Of the red cultivars in this study, Rhonda was most susceptible to PLS. The PLS epidemics in Falcon and Rhonda were best described by Gompertz models typical of a polycyclic epidemic. Further studies are needed to elucidate associations between specific betalains and their role in susceptibility to important fungal pathogens. To design a comprehensive disease management program for PLS, information on efficacy of conventional and Organic Material Review Institute–approved fungicides is also essential.

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