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Frequent soil surfactant applications influence anthracnose on an annual bluegrass research green

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Abstract

Anthracnose is a turfgrass disease caused by the fungal pathogen *Colletotrichum cereale* Manns and can cause severe damage to annual bluegrass putting greens. Most turfgrass managers use fungicides to manage anthracnose, although legislation in some locations are compelling managers to seek fungicide alternatives. This 2-yr field experiment in western Oregon evaluated different rates and application intervals of a soil surfactant—either in combination or in the absence of a spring hollow-tine aerification on anthracnose severity—on an annual bluegrass (*Poa annua* L. var. *reptans*) research green. The highest rate of the soil surfactant applied once or twice a week consistently reduced anthracnose severity in both years compared to the nontreated control, although these applications corresponded to four and eight times the monthly label rate. A quarter of the label rate applied once a week suppressed anthracnose at the peak of disease in the second year and as measured by area under disease progress curves in both years. Spring aerification had no effect on anthracnose severity. Area under volumetric water content progress curves calculated using weekly measurements at a 38-mm depth were not correlated with area under disease progress curves. The volumetric water content percentage was normally above 25%, reducing the risk of confounding between drought stress and treatments on anthracnose suppression. The highest rate of soil surfactant applied at the most frequent interval was the only treatment to receive acceptable turfgrass quality ratings over both years.

1 | INTRODUCTION

Anthracnose is a disease caused by the fungal pathogen *Colletotrichum cereale* Manns and can cause damage to cool-season turfgrass (*Poa annua* L. var. *reptans*) putting greens during periods of summer stress (Latin, 2015; Smiley, Dernoeden, & Clarke, 2005). One of the most recognizable signs of anthracnose is the presence of black acervuli on the turfgrass leaf surface (Khan & Hsiang, 2003). These acervuli produce conidia that require humid environmental conditions for survival and germination (Settle, Martinez-Espinoza, & Burpee, 2006).

In climates similar to the Pacific Northwest, annual bluegrass dominates the turfgrass sward of golf course putting greens (Smiley et al., 2005; Vargas, 2005). Therefore, the

Abbreviations: AUDPC, area under disease progress curve; AUVWCPC, area under volumetric water content progress curve; VWC, volumetric water content.

breeding of creeping bentgrass [*Agrostis stonolifera* var. *palustris* (Huds.) Farw] for anthracnose resistance is of little benefit to this region. Research focusing on cultural practices of annual bluegrass management has demonstrated the effects of irrigation, mowing heights, nitrogen fertilization, verticutting, sand topdressing, and rolling on the severity of anthracnose on annual bluegrass putting greens (Danneberger, Caroll, Vargas, & Rieke, 1995; Hempfling, Clarke, & Murphy, 2015; Inguagiato, Murphy, & Clarke, 2008, 2009, 2012; Roberts, Inguagiato, Clarke, & Murphy, 2011; Schmid, Clarke, & Murphy, 2017). With this information, turfgrass managers can develop a maintenance program that results in healthier annual bluegrass plants and less anthracnose severity, (Hempfling, Schmid, Wang, Clarke, & Murphy, 2017) as well as lowering fungicide inputs.

Despite these recent improvements in our understanding of anthracnose management on annual bluegrass, this disease remains a concern on annual bluegrass, particularly on putting greens where managers are not able to adequately implement the recommended cultural practices. Fungicides can be effective at suppressing anthracnose, (Clarke, Vincelli, Koch, & Munshaw, 2017) however fungicide resistance in the strobilurin, dimethylation inhibitors and benzimidazole chemistries have been observed (Avila-Adame, Olaya, & Köller, 2003; Latin, 2015; Wong & Midland, 2007; Wong, de la Cerda, Hernandez-Martinez, & Midland, 2008; Wong, Midland, & de la Cerda, 2007). For this reason, it would be beneficial for turfgrass managers to have alternative methods of managing anthracnose on annual bluegrass putting greens in order to reduce fungicide inputs and the risk of resistance in their annual bluegrass swards. In addition, pesticide restrictions in Europe and North America are motivating turfgrass managers to seek alternative methods for managing turfgrass diseases. Examples of restrictions include re-entry intervals times being enforced on golf courses in France (Ministère de l'agriculture et de la pêche, 2006), pesticides not being authorized when used only for cosmetic purposes in Canada (Christie, 2010), or a limited amount of fungicides being permitted for use on city-owned golf courses (San Francisco, 2019).

In 2014, following a winter dew-removal study in Corvallis, OR, there was anecdotal evidence that frequent applications of a soil surfactant reduced the severity of anthracnose on annual bluegrass putting greens (unpublished data). In this dew-removal study, an application of 19.0 L ha^{-1} of the Revolution soil surfactant (alkyl terminated block copolymer; Aquatrols, Paulsboro, NJ) applied twice a week from 1 Oct. 2013 to 31 May 2014 suggested that these applications had the potential for reducing the severity of anthracnose symptoms. While this anecdotal evidence was surprising, the main concern was the fact that the rate and frequency tested in this study amounted to eight times the recommended label rate used for typical applications of the soil surfactant and may be too cumbersome or expensive for golf course applications.

The objective of this research was to quantify the effects of different rates and frequencies of a soil surfactant on the severity of anthracnose on an annual bluegrass research green. In addition, because spring core aerification was also anecdotally observed in western Oregon to reduce anthracnose severity, a spring core aerification treatment was included in the experimental design.

2 | METHODS AND MATERIALS

2.1 | Experimental design

A field study was conducted at the Oregon State University Lewis-Brown Horticulture Farm in Corvallis, OR from 3 Feb. 2015 to 28 Sept. 2015 and again from 2 Feb. 2016 to 27 Sept. 2016. The research green used for this experiment was built in 2009 by placing 30 cm of United States Golf Association (USGA) recommended particle sized sand (United States Golf Association, 2004) on the native Malabon silty clay loam (fine, mixed, mesic Pachic Ultic Argixerolls; California Soil Resource Lab, 2019). Annual bluegrass was then established from sand-based sod (Bos Sod, Coaldale, Canada), which was laid over the constructed root zone. Anthracnose was naturally occurring in the trial, and the trial was not inoculated with *Colletotrichum cereale*.

The experimental design was a 2 × 8 randomized complete strip-plot design with four replications and a total trial area of 96 m^2. The two main factors included in the study were soil surfactant applications and spring core aerification. Soil surfactant applications were applied to a plot size of 3 m^2 and consisted of eight levels of the Revolution soil surfactant (Aquatrols, Paulsboro, NJ): 19 L ha^{-1} twice a week, 19 L ha^{-1} once a week, 19 L ha^{-1} every 2 wk, 19 L ha^{-1} every 3 wk, 19 L ha^{-1} every 4 wk, 9.5 L ha^{-1} every 2 wk, 4.75 L ha^{-1} once a week, and a nontreated control (a treatment list can be found in Table 1). These treatments were chosen to include a range of rates and frequencies, from the highest rate and most frequent application, which previously demonstrated anecdotal evidence of suppression of anthracnose (19 L ha^{-1} twice a week), to the monthly label rate divided by four and applied weekly (4.75 L ha^{-1} once a week). In both years, soil surfactant applications were made from the first week of February to the last week of September. Soil surfactant was applied using a CO_2–pressurized backpack sprayer with a handheld boom equipped with four XR80015 nozzles (25.4-cm nozzle spacing) using a carrier volume of 814 L ha^{-1} and a pressure of 280 kPa at the boom. Walking speed was calibrated with a metronome. The soil surfactant treatments were allowed to dry on the turfgrass leaves and any irrigation that did occur in the spring or summer occurred the following morning.

In order to accommodate the aerification machine (Aercore 800, John Deere, Moline, IL), spring core aerification

TABLE 1 Analysis of variance of soil surfactant applications and spring aerification treatments on area under disease progress curve (AUDPC) and disease percentage at the peak of disease on an annual bluegrass putting green in Corvallis, OR. The 2015 trial began on 3 Feb. 2015 and concluded on 28 Sept. 2015. The 2016 trial began on 2 Feb. 2016 and concluded on 27 Sept. 2016. The AUDPC was calculated from the first observation of disease (15 May and 15 July for the 2015 and 2016 trials, respectively) to the end of the trials. Stratified sampling was used to quantify the disease severity on each date. The AUDPC and percent disease data were adjusted using a cube root transformation

		2015		2016	
Source of Variation	*df*	AUDPC	Percent disease 8 Sept. 2015	AUDPC	Percent disease 27 Sept. 2016
		Pr > F			
Surfactant (S)	7	$P < .001$	$P < .001$	$P = .004$	$P = .003$
Aerification (A)	1	$P = .595$	$P = .854$	$P = .627$	$P = .291$
S × A	7	$P = .996$	$P = .937$	$P = .418$	$P = .707$

occurred as a strip plot over half of the soil surfactant treated plots, resulting in a plot size of 12 m^2. Spring core aerification consisted of either no aerification treatment or 13-mm diameter hollow-tine core aerification with USGA recommended particle sized sand backfill performed on a 51 by 51 mm spacing at a depth of 76 mm, applied on 15 April during both years of the study. The trial was repeated in a completely different area of the same research green in the second year eliminating any possibility of residual effects from the previous year.

2.2 | Turfgrass maintenance

The research green was mowed once a week from February through March at a height of 3.8 mm, five times a week from April through September at a mowing height of 2.8 mm, and clippings were removed. Fertility consisted of 4.9 kg N ha^{-1} applied every 2 wk in February and March and 9.8 kg N ha^{-1} applied every 2 wk from April through September using a compound fertilizer containing 23.7% w/w urea N and 4.3% w/w nitrate N (28% N, 2.2% P, 15% K) as well as micronutrients (0.02% B, 0.07% Cu, 0.10% Fe, 0.05% Mn, 0.05% Zn; Andersons 28–5–18, Maumee, OH). Sand topdressing was applied at a rate of 0.8 L m^{-2} once a month from May through September. Fungicides were applied as a prophylactic against Microdochium patch [*Microdochium nivale* (Fries) Samuels & Hallett (teleomorph: *Monographella nivalis*)] during months when the trial was not taking place. These included pentachloronitrobenzene (1,2,3,4,5-pentachloro-6-nitrobenzene; Turfcide 400, Amvac, Newport Beach, CA) applied at a rate of 9.2 kg a.i. ha^{-1} on 14 October 2014 and 21 October 2015 as well as propiconazole [1-[[2-(2.4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1,2,4-triazole] (Propiconazole 14.3, Control Solutions Inc., Pasadena, TX) applied at a rate of 1.0 kg a.i. ha^{-1} on 12 November 2014 and 24 November 2015. In addition to these fungicide applications, in the first year of the study, pentachloronitrobenzene was applied on 29 May 2015 at a rate of 9.2 kg a.i. ha^{-1} because of the presence of Microdochium patch. Anthracnose was observed on all four blocks of the trial on 12 June 2015 and progressed throughout the remainder of the trial. The only other fungicides applied during the trial period were curative applications of flutolanil (N-[3-propan-2-yloxyphenyl]-2-[trifluoromethyl]benzamide; ProStar, Bayer, Leverkusen, Germany) at a rate of 9.4 kg a.i. ha^{-1} applied on 11 May, 2015, 29 Apr. 2016 and 18 Aug. 2016 to suppress cool season brown patch [*Ceratobasidium cereale* D. Murray & L.L. Burpee] and fairy ring disease caused by a basidiomycete complex. Flutolanil has previously been tested on anthracnose with no suppression observed (Towers, Green, Weibel, Majumdar, & Clarke, 2002). During the summer, irrigation was applied with an overhead irrigation system set to replace 80% of the evapotranspiration every day using well water with a pH of 6.3. Drought stress was not observed on the experimental area.

2.3 | Response variables

Response variables included area under disease progress curve (AUDPC), area under volumetric water content progress curve (AUVWCPC), and turfgrass quality. Area under disease progress curve data were calculated using plot disease severity percentage quantified using stratified sampling of digital images which were collected monthly throughout the trial. Two digital subsample images were always obtained in the same location within a plot using a Sony DSC-H9 camera mounted on a 0.31-m^2 enclosed photo box with four 40-W spring lamps (TCP, Lighthouse supply, Bristol, VA). A 100-point digital grid was overlaid on each image using Sigma Scan Pro (v.5.0, SPSS, Chicago, IL) and grid counts of anthracnose severity were recorded for each image (Laycock & Canaway, 1980; Richardson, Karcher, & Purcell, 2001).

Prior to any soil surfactant applications, the average of four volumetric water content (VWC) percentage readings were collected from each plot once a week using a time domain reflectometer (Field Scout 300, Spectrum Technologies, Aurora, IL) equipped with 38-mm probes, starting the week after the date of aerification (15 Apr. of both years) and continuing through the end of the trial period (28 Sept. 2015 and 27 Sept. 2016) These data were used to calculate AUVWCPCs. Area under progress curves were calculated as determined by Shaner and Finney (1977) where the average response between observations $(y^i + y^{i+1})/2$ is multiplied by the interval of time between the observations $(t^{i+1} - t^i)$ using the formula:

$$\sum [(y^i + y^{i+1})/2]\,(t^{i+1} - t^i)$$

Turfgrass quality ratings were designated using the National Turfgrass Evaluation Program (NTEP) system of rating (Morris & Shearman, 2017) using a scale from 1 to 9, with a rating of 6 or greater being considered acceptable turfgrass quality.

2.4 | Statistical analysis

2.4.1 | Area under disease progress curve and disease percentage at the peak of disease

The two factors in the analysis were spring core aerification and soil surfactant treatment. The AUDPC data and the disease percentage at the peak of disease data did not meet the assumption of homoscedasticity within the soil surfactant treatment groups, as the variance of AUDPC and the disease percentage seemed to increase exponentially with the mean. Transforming the response variable by raising it to a particular power is a common approach used to address heteroscedasticity, especially when there is a relationship between the mean and the variance. To identify an appropriate power transformation, the Yeo–Johnson method was used (Yeo & Johnson, 2000) in R 3.4.2 (R Core Team, 2018). Then, AUDPC data and disease percentage data were adjusted using a cube root transformation. Upon transformation, *p*-values from the Brown–Forsythe test (Brown & Forsythe, 1974), also known as the Levene's test with medians, were large for both years (0.16 in 2015 and 0.55 in 2016 for the AUDPC, and 0.62 in 2015 and 0.48 in 2016 for disease percentage). This indicates that there is little to no evidence of unequal variances in either year. The model was estimated using Restricted Maximum Likelihood (Harville, 1977; Patterson & Thompson, 1971). Post-hoc tests were calculated on the pairwise differences within the spring core aerification and soil surfactant factors using Tukey's method (Littell, Milliken, Stroup, Wolfinger, & Oliver, 2006; Tukey, 1949). The experimental design analysis and post-hoc tests were performed using Proc Mixed in SAS 9.4 (SAS Institute, Cary, NC) and R (R Core Team, 2018).

2.4.2 | Area under the volumetric water content progress curve and volumetric water content percentage

The AUVWCPC data met the assumption of homogenous variance (Brown–Forsythe *p*-values in 2015 = .578 and 2016 = .377) and were therefore subjected to analysis of variance (ANOVA) using the same approach as used for the transformed AUDPC data, and Tukey's method was used to assess pairwise comparisons. Monthly data were used in a repeated measures strip-plot ANOVA of VWC percentage, and a heterogeneous AR(1) structure was used to model the correlation between repeated measurements (Littell et al., 2006). *P*-values of post-hoc pairwise comparisons were corrected for multiple comparisons using Holm's method (Holm, 1979).

2.4.3 | Turfgrass quality

The Kruskal–Wallis (Kruskal & Wallis, 1952) was used to analyze the ordinal visual turfgrass quality data and Dunn's test (Dunn, 1964) was used to assess pairwise comparisons. This type of analysis requires ignoring the strip-plot structure and treats the experiment as a randomized complete block design. Because it is often of interest to see how these treatments affect turfgrass quality at separate times throughout the year, separate tests were conducted for each month from March through September. Within each test, we calculated pairwise comparisons using Dunn's test in R and controlled family-wise error rate with Holm's method (Holm, 1979; R Core Team, 2018).

3 | RESULTS

Analysis of the 2015 and 2016 AUDPC and disease percentage at the peak of disease data resulted in a significant main effect difference for the soil surfactant treatment, while aerification and the interaction between soil surfactant and aerification were not significant (Table 1).

The highest rate of soil surfactant (19.0 L ha^{-1}) at the two highest frequencies (once and twice a week) were the only treatments that significantly suppressed anthracnose in regards to AUDPC and anthracnose percentage at the peak of disease in both years of the study (Table 1). In addition to the two highest rates and frequencies of the soil surfactant, other significant differences were observed. In the first year, 4.75 L ha^{-1} of soil surfactant applied once a week resulted in a significantly lower AUDPC compared to the nontreated control. In the second year, soil surfactant applications of 19 L ha^{-1} every 2 or 3 wk and 4.75 L ha^{-1} applied once a week suppressed anthracnose compared to the nontreated control as

TABLE 2 Main effects of soil surfactant and on area under disease progress curve (AUDPC) and disease percentage at the peak of disease on an annual bluegrass putting green in Corvallis, OR. The 2015 trial began on 3 Feb. 2015 and concluded on 28 Sept. 2015. The 2016 trial began on 2 Feb. 2016 and concluded on 27 Sept. 2016. The AUDPC was calculated from the first observation of disease (15 May and 15 July for the 2015 and 2016 trials, respectively) to the end of the trials. Stratified sampling was used to quantify the disease severity on each date. Means are back transformed from the cube root means and are averaged over the aerification treatments

Soil surfactant	2015 AUDPC	8 Sept. 2015 Percent disease	2016 AUDPC	27 Sept. 2016 Percent disease
19.0 L ha^{-1} twice a wk	1.6d[a]	0.08c	0b	0.00b[b]
19.0 L ha^{-1} once a wk	28.6cd	3.61b	0.6b	0.00b[b]
19.0 L ha^{-1} every 2 wk	97.6abc	10.40ab	0.1b	0.01b
19.0 L ha^{-1} every 3 wk	111.6abc	12.83ab	2.8b	0.02b
19.0 L ha^{-1} every 4 wk	176.5ab	17.81ab	6.9ab	0.66ab
9.5 L ha^{-1} every 2 wk	144.3ab	16.20ab	8.6ab	0.43b
4.75 L ha^{-1} once a wk	73.9bc	6.25ab	0.4b	0.02b
Not treated control	293.2a	23.31a	112.7a	6.74a

[a]Means in the same column followed by the same letter are not significantly different according to Tukey's method ($\alpha \leq .05$). The letters were constructed under the assumption that all groups had the same variance.

[b]All of the data points for surfactant treatments 19.0 L ha^{-1} applied once or twice a wk resulted in the complete absence of disease and therefore no variance is associated with these data.

TABLE 3 Analysis of variance of soil surfactant applications (applied from the trial start date to the end of the trial) and spring aerification treatments (occurred on 15 Apr. in both years) on volumetric water content percentage (VWC %) and area under volumetric water content progress curve (AUVWCPC; calculated from 15 Apr. 2015–28 Sept. 2015 and 15 Apr. 2016–27 Sept. 2016 for the 2016 and 2016 trials, respectively) on an annual bluegrass research green in Corvallis, OR. The 2015 trial began on 3 Feb. 2015 and concluded on 28 Sept. 2015, and the 2016 trial began on 2 Feb. 2016 and concluded on 27 Sept. 2016

		Repeated measures fixed effects for VWC %		AUVWCPC	
Source of variation	*df*	2015	2016	2015	2016
Surfactant (S)	7	$P = .015$	$P = .003$	$P = .029$	$P = .018$
Aerification (A)	1	$P = .674$	$P = .147$	$P = .781$	$P = .150$
S × A	7	$P = .165$	$P = .643$	$P = .110$	$P = .162$
Month (M)	5	$P < .001$	$P < .001$		

measured by AUDPC and at the peak of disease. The 9.5 L ha^{-1} of soil surfactant also significantly reduced anthracnose at the peak of disease in the second year.

The repeated measures strip-plot analysis indicated a significant main effect difference for the soil surfactant treatment for VWC percentage in both years, whereas aerification and the interaction between soil surfactant treatments and aerification were not significant in either year. Analysis of variance of the AUVWCPC data also indicated a significant main effect difference for the soil surfactant treatment while aerification and the interaction between soil surfactant treatments and aerification were not significant in either year (Table 2).

Soil surfactant applications of 19 L ha^{-1} twice a week were in the group with lowest VWC percentage on two dates in 2015. In 2016, it was difficult to establish a pattern between the soil surfactant treatments and VWC percentage, although on four out of six dates, the soil surfactant applied at 19 L ha^{-1} either once or twice a week was in the group with the lowest VWC percentage. In each year, on one date out of six, the nontreated control had a higher VWC percentage than when the soil surfactant was applied at 19 L ha^{-1} either once or twice a week. The soil surfactant label rate of 19 L ha^{-1} applied every 4 wk was in the group with the highest VWC percentage on two out of six dates in 2015 and four out of six dates in 2016. In 2016, half of the label rate (9.5 L ha^{-1}) applied every 2 wk resulted in a lower VWC percentage than the label rate on two dates.

The analysis of the AUVWCPC summary statistic resulted in a significant main effect difference for the AUVWCPC data in both years. The Tukey's method for pair-wise comparisons only found a significant separation of the means in 2016 (Table 3). In 2016, applications of 19 L ha^{-1} once a week resulted in a lower AUVWCPC value compared to 19 L ha^{-1} every 4 wk. There was no correlation between the AUDPC and the AUVWCPC in either 2015 or 2016 (R^2 = .044 and .005, respectively) suggesting that anthracnose suppression is not tied to any effects on VWC percentage by the soil surfactant.

Regarding turfgrass quality in 2015 and 2016, there were only a few dates where a separation by the Dunn's test existed. When significant pair-wise comparison differences in turfgrass quality did occur, only the applications of 19 L ha^{-1} of the soil surfactant applied either once or twice a week were different from the nontreated control (Tables 4 and 5). On 18 May 2015, 25 Mar. 2016, and 14 June 2016, some applications of 19 L ha^{-1} soil surfactant twice a week resulted in a lower turfgrass quality compared to the control because of a loss of green color. On the 11 July 2015, 14 Aug. 2015, and 8 Sept. 2015 rating dates, some applications of 19 L ha^{-1} soil surfactant either once or twice a week resulted in a higher turfgrass quality compared to the control because of less anthracnose on those plots compared to the nontreated control (Tables 4 and 5).

4 | DISCUSSION

On plots where soil surfactants were not applied in each year, anthracnose symptoms were expressed to a higher level in 2015 with an average of 23.3% compared to 6.7% anthracnose in 2016 (Table 1). Anthracnose symptoms also appeared earlier in 2015 (starting on 15 May 2015) than in 2016 (starting on 15 July 2016). In 2015, the presence of anthracnose was observed on at least one plot per treatment combination by the 21 June rating date. In 2016, the presence of anthracnose was observed on at least one plot for each soil surfactant treatment by the 12 September rating date. The weather conditions during the trial period were markedly different between 2015 and 2016, which may explain the differences in the observed anthracnose severity between years (Table 6).

Notably, there was a difference in total rainfall received from the months of April through September in each year (3 mm in 2015 compared to 122 mm in 2016). Even though the irrigation in this study was linked to the evapotranspiration observed on site, the increased rainfall in 2016 was indicative of more mild conditions. This perhaps explains why there were less anthracnose symptoms and why symptoms appeared later in 2016 than in 2015. Previous research has shown an increase in the severity of anthracnose on annual bluegrass when available soil moisture was decreased from 100% field capacity down to 27.7 and 5.4% field capacity (Danneberger et al., 1995), and higher rates of irrigation are reported to decrease the susceptibility of annual bluegrass to anthracnose (Roberts et al., 2011). In addition, the soil surfactant only had a limited effect on the AUVWCPC data, and this effect was not correlated to the AUDPC data. Furthermore, the average monthly maximum temperatures during the months of June and July in 2015 were higher (28 and 29 °C, respectively) compared to temperatures observed in June and July 2016 (24 and 25 °C, respectively; Table 6). The optimum

TABLE 4 Letter diagrams of main effects of soil surfactant applications (applied from start to end of trial) and spring aerification treatments on volumetric water content percentage and area under volumetric water content progress curve (AUVWCPC; calculated from 15 Apr. to 28 Sept. 2015) on an annual bluegrass research green in Corvallis, OR. Trials were from 3 February to 28 September and 2 February to 27 September in 2015 and 2016, respectively

	2015							2016						
	Volumetric water content percentage													
Soil Surfactant[b]	25 Apr.	28 May	25 June	31 July	24 Aug.	28 Sept.	AUVWCPC[c]	26 Apr.	24 May	27 June	28 July	29 Aug.	27 Sept.	AUVWCPC
19.0 L ha^{-1} twice a wk	30b[d]	29b	32a	37a	37a	20a	4,586a	33b	28abc	21ab	30a	36ab	28ab	4,368ab
19.0 L ha^{-1} once a wk	36ab	34ab	35a	37a	37a	24a	5,051a	33b	24c	18b	26a	33b	27ab	4,145b
19.0 L ha^{-1} every 2 wk	34ab	34ab	35a	39a	37a	22a	4,967a	38ab	33ab	19b	28a	38ab	30ab	4,695ab
19.0 L ha^{-1} every 3 wk	31ab	33ab	34a	38a	38a	24a	4,907a	35ab	28abc	18b	27a	34b	27ab	4,284ab
19.0 L ha^{-1} every 4 wk	37a	36a	35a	38a	38a	24a	5,148a	41a	35a	25ab	32a	41a	35a	5,158a
9.5 L ha^{-1} every 2 wk	36a	35a	36a	39a	39a	25a	5,192a	37ab	26bc	20ab	26a	36ab	26b	4,322ab
4.75 L ha^{-1} once a wk	32ab	31ab	33a	36a	36a	22a	4,669a	40a	34a	22ab	29a	37ab	29ab	4,776ab
Nontreated control	35ab	35a	36a	40a	40a	24a	5,265a	39ab	27abc	27a	31a	37ab	31ab	4,865ab

[a]Means in the same column followed by the same letter are not significantly different according to Holm's method ($\alpha \leq .05$).

TABLE 5 Effects of soil surfactant applications (applied as Revolution, Aquatrols, Paulsboro, NJ) and spring aerification treatments (a strip-plot aerification treatment was performed on 15 Apr. 2015) on turfgrass quality ratings on an annual bluegrass research green in Corvallis, OR. Trial began on 3 February 2015 and concluded on 28 September 2015. Columns within month represent the mean turfgrass quality rating based on a ranking of 1–9 with 6 or greater considered acceptable

Aerified	Soil surfactant	11 Mar.	25 Apr.	18 May	12 June	11 July	14 Aug.	8 Sept.
Yes	19.0 L ha^{-1} twice a wk	8.0a[a b]	6.8a	7.1b	6.0a	7.0ab	6.8a	6.5a
Yes	19.0 L ha^{-1} once a wk	8.0a	6.4a	7.4ab	6.0a	7.3a	5.9ab	5.0ab
Yes	19.0 L ha^{-1} every 2 wk	8.0a	7.0a	7.5a	5.8a	5.4ab	5.1abc	4.4ab
Yes	19.0 L ha^{-1} every 3 wk	8.0a	7.0a	7.5a	6.0a	5.5ab	5.1abc	4.3ab
Yes	19.0 L ha^{-1} every 4 wk	8.0a	7.0a	7.5a	5.9a	5.1ab	4.8abc	4.0ab
Yes	9.5 L ha^{-1} every 2 wk	8.0a	7.0a	7.5a	5.9a	5.1ab	5.0abc	4.1ab
Yes	4.75 L ha^{-1} once a wk	8.0a	7.0a	7.5a	6.3a	6.0ab	5.1abc	4.6ab
Yes	No soil surfactant	8.0a	7.0a	7.5a	5.1a	4.8ab	3.8bc	3.4b
No	19.0 L ha^{-1} twice a wk	8.0a	6.3a	7.3ab	6.3a	6.8ab	6.9a	6.8a
No	19.0 L ha^{-1} once a wk	8.0a	6.4a	7.5a	6.0a	7.3a	5.5abc	5.0ab
No	19.0 L ha^{-1} every 2 wk	8.0a	6.6a	7.5a	5.8a	5.4ab	4.9abc	4.4ab
No	19.0 L ha^{-1} every 3 wk	8.0a	6.5a	7.5a	6.3a	6.0ab	4.8abc	4.4ab
No	19.0 L ha^{-1} every 4 wk	8.0a	6.4a	7.5a	5.6a	4.9ab	4.4abc	3.9ab
No	9.5 L ha^{-1} every 2 wk	8.0a	6.5a	7.5a	6.0a	5.3ab	5.0abc	4.1ab
No	4.75 L ha^{-1} once a wk	8.0a	6.5a	7.5a	5.8a	5.4ab	5.3abc	4.4ab
No	No soil surfactant	8.0a	6.4a	7.5a	5.1a	4.5b	3.6c	3.5b

[a]Corrections within the month were applied using Holm's method within each month.
[b]The letters in each column indicate significant differences between the treatments after using Dunn's test and controlling for multiple comparisons within each month using Holm's method ($\alpha \leq 0.05$).

TABLE 6 Effects of soil surfactant applications (applied as Revolution, Aquatrols, Paulsboro, NJ) at the applications intervals indicated) and spring aerification treatments (a strip-plot aerification treatment was performed on 15 Apr. 2016) on turfgrass quality ratings on an annual bluegrass research green in Corvallis, OR. Trial began on 2 February 2016 and concluded on 27 September 2016. Columns within month represent the mean turfgrass quality rating based on a ranking of 1–9 with 6 or greater considered acceptable

Aerified	Soil surfactant	25 Mar.	16 Apr.	15 May	14 June	18 July	29 Aug.	27 Sept.
Yes	19.0 L ha^{-1} twice a wk	6.0b[a b]	7.0a	6.9a	6.1b	6.0a	6.0a	6.5a
Yes	19.0 L ha^{-1} once a wk	7.0a	7.0a	7.0a	7.0a	6.6a	5.8a	6.8a
Yes	19.0 L ha^{-1} every 2 wk	7.0a	7.0a	7.0a	7.0a	7.1a	6.1a	6.5a
Yes	19.0 L ha^{-1} every 3 wk	7.0a	7.0a	7.0a	7.0a	6.0a	6.1a	6.5a
Yes	19.0 L ha^{-1} every 4 wk	7.0a	7.0a	7.0a	7.0a	6.6a	5.5a	4.8a
Yes	9.5 L ha^{-1} every 2 wk	7.0a	7.0a	6.8a	7.0a	6.5a	5.3a	5.5a
Yes	4.75 L ha^{-1} once a wk	7.0a	7.0a	7.0a	7.0a	6.9a	6.0a	6.3a
Yes	No soil surfactant	7.0a	7.0a	7.0a	7.0a	6.4a	5.1a	3.3a
No	19.0 L ha^{-1} twice a wk	6.0b	7.0a	6.8a	6.3ab	6.0a	6.3a	6.8a
No	19.0 L ha^{-1} once a wk	7.0a	7.0a	7.0a	6.8ab	6.6a	6.5a	6.8a
No	19.0 L ha^{-1} every 2 wk	7.0a	7.0a	7.0a	7.0a	6.8a	6.1a	6.3a
No	19.0 L ha^{-1} every 3 wk	7.0a	7.0a	7.0a	7.0a	5.6a	5.8a	5.5a
No	19.0 L ha^{-1} every 4 wk	7.0a	7.0a	7.0a	7.0a	6.5a	5.6a	4.5a
No	9.5 L ha^{-1} every 2 wk	7.0a	7.0a	7.0a	7.0a	6.5a	5.8a	5.0a
No	4.75 L ha^{-1} once a wk	7.0a	7.0a	7.0a	7.0a	6.5a	6.6a	6.3a
No	No soil surfactant	7.0a	7.0a	7.0a	7.0a	6.3a	5.0a	3.5a

[a]Corrections within the month were applied using Holm's method within each month.
[b]The letters in each column indicate significant differences between the treatments after using Dunn's test and controlling for multiple comparisons within each month using Holm's method ($\alpha \leq 0.05$).

TABLE 7 Weather data summary for the Lewis-Brown Turfgrass Research Farm in Corvallis, OR for the spring and summer of 2015 and 2016

	Rainfall[a]		Temperature					
			Min		Max		Average	
	mm		°C					
Month	2015	2016	2015	2016	2015	2016	2015	2016
Apr.	0.9	72.3	4.2	6.5	16.2	19.1	9.8	12.3
May	0.9	14.8	8.4	9.0	20.6	21.0	13.9	14.7
June	0.0	12.9	11.6	10.8	27.5	23.9	19.4	16.9
July	0.0	14.2	13.0	12.4	29.3	25.3	20.7	18.5
Aug.	0.1	0.0	12.8	12.0	28.2	28.4	20.1	20.0
Sept.	0.8	8.0	9.1	9.1	23.2	23.3	15.8	15.9

[a]Total rainfall was 2.7 and 122.0 mm in 2015 and 2016, respectively.

infection temperature for *Colletotrichum cereale* on annual bluegrass has been reported to be between 30 and 33 °C (Bolton & Cordukes, 1981), which may further explain why there was more anthracnose observed in 2015 compared to 2016.

The highest rate of the soil surfactant tested (19 L ha^{-1}) applied either once or twice a week resulted in suppression of anthracnose compared to the nontreated control in both years of the study, as measured by AUDPC and disease percentage at the peak of disease. These rates of soil surfactant total 76 and 152 L ha^{-1} per month compared to a label rate of 19 L ha^{-1} per month. These higher rates and frequencies would probably not be considered practical from a logistical or an economic standpoint. Coincidentally, only the monthly label rate of 19 L ha^{-1} applied every 4 wk did not suppress anthracnose in either year of the experiment. Half of the label rate (9.5 L ha^{-1}), applied every 2 wk, suppressed anthracnose at the peak of the disease in the second year. A quarter of the label rate (4.75 L ha^{-1}) applied once a week resulted in a lower AUDPC in both years of the study and at the peak of disease in the second year.

The fact that a reduction in anthracnose severity was observed when fractions of the monthly label rate of the soil surfactant were applied at higher frequencies than the label rate, while the monthly label rate never suppressed anthracnose in this study, suggests that frequency of application may be more important than quantity of product applied. Indeed, the 19 L ha^{-1} rate applied every 2 wk did not result in less anthracnose than the 9.5 L ha^{-1} rate applied every 2 wk, and the same is true for the 19 L ha^{-1} of soil surfactant applied once a week compared to 4.75 L ha^{-1} applied once a week. No lower rate of soil surfactant was applied twice a week to compare with the 19 L ha^{-1} rate applied twice a week. The soil surfactant applications of 4.75 L ha^{-1} applied once a week and the 9.5 L ha^{-1} applied every 2 wk may provide options for turfgrass managers seeking to reduce anthracnose without increasing the product cost of using a higher rate of soil surfactant once a month, though labor costs are likely to increase. However, further research is needed to determine how these rates and frequencies would compare to the monthly rate regarding the benefits of soil surfactants to prevent localized dry spot or soil moisture uniformity (Schiavon, Leinauer, Serena, Maier, & Sallenave, 2014).

Although mechanisms of *Colletotrichum cereale* inhibition by the soil surfactant were not explored, the same soil surfactant used in this experiment was anecdotally observed to reduce dew for a few days post application, both in this study and in a previous experiment (Mattox, Kowalewski, & McDonald, 2014). A growth chamber study has demonstrated that increasing the duration of leaf wetness can increase the amount of infection on annual bluegrass by *Colletotrichum cereale* (Vargas, Danneberger, & Jones, 1993), therefore it could be postulated that dew removal by soil surfactants may play a role in the suppression of anthracnose. A study exploring the role that an organosilicone surfactant had on the infection of the *Colletotrichum* species *truncatum* to infect hemp sesbania (*Sesbania exaltata*) across different levels of dew demonstrated that the surfactant led to an increase in disease under delayed or no dew when added to a conidia emulsion (Boyette, Hoagland, & Weaver, 2007). The authors of that study hypothesized that germination of conidia and the formation of appressoria was stimulated by the surfactant, but that dew or corn oil helped to prevent desiccation of the conidia before infection occurred (Boyette et al., 2007). It is possible that the surfactant in this current study stimulated fungal growth and reduced dew to levels unfavorable to the fungi. Dew removal was not quantified in this study; the role of dew removal, however, and any effects on conidial germination or appressoria formation by soil surfactants may merit further investigation as a mechanism of anthracnose suppression on turfgrass.

Spring aerification treatment did not influence the severity of anthracnose in either year in this study, as calculated by AUDPC or disease percentage. Anthracnose is suggested to be a disease that occurs more frequently on turfgrass under environmental stress (Danneberger et al., 1995) and has been reported to be more severe under compacted conditions (Smiley et al., 2005; Vargas, 2005). The primary benefit of aerification on a summer disease occurring on a sand-based putting green would likely be a decrease in bulk density and an increase in rooting depth or density (Atkinson, McCarty, & Bridges, 2012; Fry & Huang, 2004), although bulk density and rooting depth were not quantified in this study.

The experimental area was irrigated to avoid drought stress and the average VWC per treatment was usually above 25%. This VWC% is likely higher than would be common for golf course putting greens, however this avoided confounding results between drought stress and treatments. Aerification was not found to influence AUVWCPC or VWC percentage. The process of aerification that removes cores with sand replacement has been linked to a lower VWC percentage (Rowland, Cisar, Snyder, Sartain, & Wright, 2009) and aerification has been shown to lower VWC percentage on a sand-capped Kentucky bluegrass site mown at 2.5 cm (Andersons, Rimi, Richardson, Macolino, & Karcher, 2014). Maintaining the green in this study with a VWC usually above 25% may have prevented significant differences to be observed among the aerification treatments.

Anthracnose is often associated with turfgrass under stress (Latin, 2015; Smiley et al., 2005) and has been shown to increase when turfgrass is under drought stress (Danneberger et al., 1995). In this study, there was no correlation between AUVWCPC and AUDPC. One benefit of maintaining the research green with adequate moisture throughout the trial was avoiding drought stress, which may have otherwise had an influence on anthracnose severity (Danneberger et al., 1995). Had drought stress and a correlation between AUVWCPC and AUDPC occurred, there could have been confounding between drought stress and treatments, which would make it more difficult to attribute any suppression of anthracnose to the treatments.

The only treatments that resulted in a turfgrass quality rating that would be considered acceptable for putting green turf in both years of the study was the highest rate of soil surfactant (19 L ha^{-1}) applied at the highest frequency (twice a week), regardless of aerification treatment. The other treatment combinations resulted in levels of anthracnose severity that would not be acceptable for golf course putting greens. The 19 L ha^{-1} soil surfactant rate at the twice a week frequency also resulted in a loss of green color. This loss in green color is in contrast to an increase in green color in bermudagrass mown at 1.5 cm and irrigated under drought stress when the same soil surfactant was applied monthly at 20 L ha^{-1} in New Mexico (Serena, Sportelli, Sevostianova, Sallenave, & Leinauer, 2018). The loss of green color in this current study may have been because the soil surfactant was applied at nearly eight times the amount per month as was applied in the New Mexico study.

5 | CONCLUSIONS

The highest rate (19 L ha^{-1}) of soil surfactant applied at the two highest frequencies (once or twice a week) consistently reduced the severity of anthracnose compared to the nontreated control on a sand-based annual bluegrass research green in western Oregon in 2015 and 2016. Only the 19 L ha^{-1} soil surfactant application applied twice a week resulted in acceptable turfgrass quality in both years. This application suppressed anthracnose more than the once a week application in 2015, although these higher frequencies also resulted in a loss of green color. These applications would probably not be considered practical from a logistical or an economic standpoint for turfgrass managers. Half of the label rate applied every 2 wk suppressed anthracnose at the peak of the disease in the second year. A quarter of the label rate applied once a week suppressed anthracnose at the peak of disease in the second year and as measured by AUDPC in both years. These later two rates and frequencies would apply the same amount of product as the label rate per month and may provide options for turfgrass managers seeking to reduce anthracnose in combination with other best management practices. Results suggest that future research into how soil surfactants could be used to reduce the amount of traditional fungicides applied to control anthracnose on annual bluegrass putting greens is warranted.

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