Effects of Soil Type, Source of Silicon, and Rate of Silicon Source on Development of Gray Leaf Spot of Perennial Ryegrass Turf

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ABSTRACT

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Silicon amendments have been proven effective in controlling fungal diseases of various crops. However, effects of silicon amendments on gray leaf spot (*Magnaporthe oryzae*) of perennial ryegrass are not known. Studies were conducted in controlled-environment chambers and microplots where perennial ryegrass pots were buried among perennial ryegrass turf to determine the effects of silicon amendments on gray leaf spot development. Plants were grown in two soil types: peat:sand mix (soil Si = 5.2 mg/liter) and Hagerstown silt loam (soil Si = 70 mg/liter). Both soil types were amended with two sources of silicon—wollastonite and calcium silicate slag—at 0, 0.5, 1, 2, 5, and 10 metric tons/ha and 0, 0.6, 1.2, 2.4, 6, and 12 metric tons/ha, respectively. Nine-week-old perennial ryegrass was inoculated with *M. oryzae*. Gray leaf spot incidence and severity were assessed 2 weeks after inoculation. Gray leaf spot incidence and severity of perennial ryegrass significantly decreased by different rates of wollastonite and calcium silicate slag applied to both soils under both experimental conditions. Tissue silicon content increased consistently with increasing amount of silicon in the soils, while disease incidence decreased consistently with increasing tissue silicon content in all four soil and source combinations under both experimental conditions. These findings suggest that silicon amendments may be utilized in integrated gray leaf spot management programs on perennial ryegrass.

Additional keywords: *Lolium perenne*, silicon, turfgrass

Gray leaf spot, caused by *Magnaporthe oryzae* Couch, is a serious disease of perennial ryegrass (*Lolium perenne* L.) turf. Severe outbreaks of gray leaf spot have occurred on golf course fairways in various regions of the United States in recent years, resulting in extensive loss of turf (25,36,43,44). Cultural management practices often do not provide adequate control of gray leaf spot due to rapid development of the disease, high susceptibility of currently available cultivars (45), and host susceptibility at all stages of development. Currently, fungicides are considered to be the best method available for managing gray leaf spot (42); however, turf managers often prefer employing integrated disease management strategies with major emphasis on cultural practices coupled with chemical approaches that are cost effective.

Although silicon (Si) is the second most abundant element after oxygen in the earth's crust, certain soils tend to be low in plant-available silicon (12). Low-silicon soils are typically highly weathered,

leached, acidic, and low in base saturation. Thus Oxisols and Ultisols can be quite low in soluble silicon (22). Histosols with an organic matter content greater than 80%, and thus low in mineral content, are also deficient in plant-available silicon (40). Soils comprised mainly of quartz sand (SiO₂), such as sandy Entisols, are also very low in plant-available Si (12). Repeated cropping of rice can also reduce the level of plant-available silicon to the point that supplemental silicon application is required for maximum production (19). These soils may be found in some golf courses, athletic fields, and home lawns where perennial ryegrass is cultivated. In addition, repeated cropping of perennial ryegrass and removal of grass clippings may reduce the level of plant-available Si in these soils.

Silicon amendments have been proven effective in controlling both soilborne and foliar fungal diseases of several crops including turfgrass. In rice, silicon reduces the severity of several economically important diseases, such as blast (*Magnaporthe grisea* (Hebert) Barr), brown spot (*Cochliobolus miyabeanus* (Ito & Kuribayashi in Ito) Drechs. ex Dastur), stem rot (*Magnaporthe salvinii* (Cattaneo) Kraus & Webster), leaf scald (*Monographella albescens* (Thumen) Parkinson, Sivanesan & Booth), and sheath blight (*Thanatephorus cucumeris* (Frank) Donk), with improved

yield and quality (14,16,35,47). Application of calcium silicate slag and other sources of silicon has become a routine disease management practice in many rice-growing countries including the United States. Studies on greenhouse-grown cucumbers have shown that silicon added directly to hydroponic solutions can offer defense against powdery mildew (*Sphaerotheca fuliginea* (Schlechtend.) Pollacci) and Pythium root rot (10,11,29,30). The greenhouse industry in the Netherlands applies silicon directly into nutrient solutions for cucumber and rose production, and growers have reported better protection against powdery mildew and other diseases (4,48,49). Silicon amendments also have been shown to reduce several diseases of turfgrass. Hamel and Heckman (24) demonstrated that powdery mildew incidence in Kentucky bluegrass was reduced by silicon amendments. Severity of dollar spot (*Sclerotinia homoeocarpa* Bennett) and brown patch (*T. cucumeris*) decreased due to silicon fertilization in creeping bentgrass (23,46). Datnoff and Nagata (13) demonstrated that silicon amendments significantly reduced the area under the disease progress curve (AUDPC) for gray leaf spot of St. Augustinegrass (*Stenotaphrum secundatum* Walt.) between 19 and 78% among several cultivars in the greenhouse. Brecht et al. (6) reported that

Table 1. Chemical composition of silicon sources^a

Element	Calcium silicate slag	Wollastonite
Insoluble phosphoric acid (%)	2.8	0.0
Water soluble K ₂ O (%)	0.8	0.0
Al (mg/kg)	22400.0	5292.0
Ca (mg/kg)	296000.0	314286.0
Fe (mg/kg)	2000.0	1400.0
Mg (mg/kg)	1800.0	13872.0
Mn (mg/kg)	600.0	<775.0
S (mg/kg)	2800.0	0.0
B (mg/kg)	100.0	0.0
Cu (mg/kg)	30.0	0.0
Zn (mg/kg)	30.0	0.0
Co (mg/kg)	10.0	0.0
Mo (mg/kg)	50.0	0.0
SiO ₂ (%)	43.4	50.0
Na ₂ O (%)	0.0	0.2

^a Elemental contents of sources were determined using the methods of the Association of the Fertilizer and Phosphate Chemists (AFPC) and the Association of the Official Analytical Chemists (AOAC).

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silicon alone, chlorothalonil alone, or silicon and chlorothalonil combined reduced the AUDPC of gray leaf spot of St. Augustinegrass turf by 7 to 68% compared with the untreated control. They concluded that amendments with silicon may be an option to reduce gray leaf spot development of St. Augustinegrass in newly sprigged fields. Datnoff and Rutherford (15) showed that silicon amendments enhanced resistance of bermudagrass to leaf spotting and melting out caused by *Bipolaris cynodantis* (Marignoni) Shoemaker.

The mechanism by which silicon increases disease resistance remains poorly understood. Silicification of epidermal cells (26,27,41) and the formation of a cuticle-silica double layer in the apoplast (50) preventing fungal penetration and colonization are hypotheses linked to the

silicon-mediated resistance. Several studies have shown a more complex cellular mechanism that involves an active role of silicon than the simple formation of a physical barrier to penetration by the fungus. Bélanger et al. (3) showed an active role of silicon in wheat resistance to powdery mildew (*Blumeria graminis* f. sp. *tritici*). They reported that epidermal cells of silicon-treated wheat plants reacted to the pathogen attack by powdery mildew with specific defense reactions including papilla formation, production of callose, and release of electron-dense osmiophilic material identified by cytochemical labeling as glycosylated phenolics. Similarly, marked fungal hyphal alterations of *M. oryzae* in rice were observed, and were surrounded by amorphous material that were believed to be phenolic-like (31). Furthermore, silicon has been shown to increase the amount of pathogenesis-related defense compounds such as phenolics, peroxidases, chitinases, and PR-1 proteins when challenged with fungal

pathogens (9,11,30). Flavonoids and momilactone phytoalexins were found to be produced in both dicots and monocots, respectively, when fertilized with silicon and challenge inoculated by the pathogen in comparison to nonfertilized with silicon and challenge inoculated by the pathogen. These antifungal compounds also appear to be playing a major role in plant disease suppression (21,32). The enhanced resistance to disease in crops has been correlated with the applied amount of silicon and with the concentration of silicon in tissue of rice, sugarcane, St. Augustinegrass, and bermudagrass (6,13,15,17,28,34).

Effects of silicon amendments on gray leaf spot (*M. oryzae*) of perennial ryegrass are not known. Rice, which is known to be responsive to silicon fertilization, has been observed to be nonresponsive when grown in certain soils (33). Datnoff et al. (14) attributed this failure to the use of low rates of silicon fertilizers or to soils that were not deficient in plant-available silicon. Therefore, soil type may influence the

Table 2. Average ambient temperature and relative humidity (RH) for 2 weeks following inoculation in microplot experiments

Date	Ave. temp. (°C)	Ave. RH (%)
Trial 1		
Inoculation on 14 Jun 04		
15-Jun	22.1	81.7
16-Jun	22.8	81.1
17-Jun	23.1	86.0
18-Jun	22.9	85.7
19-Jun	21.1	74.2
20-Jun	15.5	61.0
21-Jun	15.3	60.8
22-Jun	20.4	71.3
23-Jun	20.5	69.9
24-Jun	19.4	67.1
25-Jun	19.2	75.9
26-Jun	18.1	86.0
27-Jun	16.1	62.5
28-Jun	16.3	71.5
Trial 2		
Inoculation on 23 Jul 04		
24-Jul	20.8	89.3
25-Jul	17.5	73.2
26-Jul	18.9	85.1
27-Jul	18.1	96.7
28-Jul	18.4	100.0
29-Jul	17.2	96.7
30-Jul	19.7	85.6
31-Jul	22.3	93.3
1-Aug	21.6	96.0
2-Aug	22.8	86.8
3-Aug	21.9	86.4
4-Aug	23.3	76.8
5-Aug	20.1	90.4
6-Aug	16.7	74.8
Trial 3		
Inoculation on 6 Sep 04		
7-Sep	17.4	86.3
8-Sep	20.4	89.2
9-Sep	19.8	98.8
10-Sep	20.0	93.4
11-Sep	18.5	79.3
12-Sep	17.2	84.3
13-Sep	19.6	84.0
14-Sep	18.8	83.8
15-Sep	17.8	92.2
16-Sep	17.4	90.0
17-Sep	19.6	90.0
18-Sep	17.7	100.0
19-Sep	14.8	69.9
20-Sep	12.1	66.8

Table 3. Effects of soil type, source, and rate of silicon application on gray leaf spot incidence^a

Source of variation	dfN	dfD	P > F
Controlled-environment chamber experiments			
Trial 1			
Soil	1	7.9	0.0
Source	1	4.5	0.1
Soil × source	1	4.1	0.3
Rate	5	27.9	<0.0
Source × rate	5	23.0	0.2
Soil × source × rate	5	23.0	0.1
Trial 2			
Soil	1	2.9	0.2
Source	1	3.1	0.2
Soil × source	1	29.9	0.4
Rate	5	27.0	<0.0
Source × rate	5	30.1	0.1
Soil × source × rate	5	29.9	0.2
Trial 3			
Soil	1	51.0	<0.0
Source	1	3.1	0.1
Soil × source	1	3.2	0.1
Rate	5	48.9	<0.0
Source × rate	5	48.8	0.8
Soil × source × rate	5	48.7	0.1
Microplot experiments			
Trial 1			
Soil	1	9.1	0.2
Source	1	9.1	1.0
Soil × source	1	9.1	0.2
Rate	5	57.9	<0.0
Source × rate	5	57.9	0.1
Soil × source × rate	5	57.9	0.0
Trial 2			
Soil	1	54.0	0.0
Source	1	54.0	0.7
Soil × source	1	54.0	0.0
Rate	5	15.0	0.0
Source × rate	5	54.0	0.2
Soil × source × rate	5	54.0	0.7
Trial 3			
Soil	1	13.2	0.1
Source	1	9.9	0.5
Soil × source	1	9.9	0.3
Rate	5	32.5	0.0
Source × rate	5	30.4	0.5
Soil × source × rate	5	30.4	0.2

^a dfN = numerator degrees of freedom; and dfD = denominator degrees of freedom.

effects of silicon amendments on gray leaf spot of perennial ryegrass. Although several sources of silicon have been utilized quite extensively, their concentrations, solubility of silicon, and the content of other elements varied widely. This study investigated the effects of soil type, source of silicon, and rate of silicon application, on incidence and severity of gray leaf spot in perennial ryegrass turf.

MATERIALS AND METHODS

Experimental design. Experiments were conducted in controlled-environment

chambers and microplots. The experiments were laid out as split-split-plot designs with soil type as the main-plot factor, source of silicon as the split-plot factor, and rate of silicon as the split-split-plot factor. The soil types used were: (i) peat:sand mix, created by mixing peat (Fafard mix no. 2, Griffin Greenhouse and Nursery Supplies, Leola, PA) and sand by volume (50:50); and (ii) soil collected from Joseph A. Valentine Turfgrass Research Center of Pennsylvania State University, which is described as Hagerstown silt loam. Fafard no. 2 contains 55% peat

moss, 20% perlite, and 25% vermiculite. Hagerstown silt loam is an Alfisol described as fine, mixed, mesic, typic hapludalfs (5). Peat:sand mix contained a soil silicon level of 5.2 mg/liter with a soil pH of 6.3, while Hagerstown silt loam had a soil silicon level of 70 mg/liter and a soil pH of 7.3. Both soil types were amended with two commercially available sources of silicon: (i) calcium silicate slag (Calcium Silicate Corporation, Lake Harbor, FL) and (ii) wollastonite (Vansil no. 10) (R. T. Vanderbilt, Norwalk, CT). The chemical analyses of wollastonite and calcium silicate slag as determined by the manufacturer using the methods of AFPC (2) and AOAC (1) are provided in Table 1. Wollastonite typically contains 48 to 50% SiO₂, whereas calcium silicate slag, a by-product of elemental P production, contains 43.3%. The difference between the levels of SiO₂ in the two sources was adjusted by using 1.2 times more calcium silicate slag than wollastonite for comparison of the two sources. The soils were amended at the rates of 0, 0.5, 1, 2, 5, and 10 metric tons/ha and 0, 0.6, 1.2, 2.4, 6, and 12 metric tons/ha with wollastonite and calcium silicate slag, respectively. Each treatment was replicated four times, and trials were conducted three times at different periods for both controlled-environment and microplot experiments. The three trials for each experimental condition will be referred to as trial 1, trial 2, and trial 3 throughout the manuscript.

Amendment of soil with silicon and plant culture. The amount of silicon added was computed based on the surface area of the pot (diameter of the pot 10.2 cm). Silicon was incorporated into soil by hand-mixing the silicon products thoroughly with approximately 630 cm³ of soil that filled a plastic pot. Legacy II perennial ryegrass was seeded at the rate of 20 g/m² and maintained in the greenhouse. Three-week-old plants were fertilized with a water-soluble fertilizer (20% N, 8.8% P, 16.6% K, Jack's classic all-purpose water soluble plant food, J. R. Peters Inc., Allentown, PA) to field capacity (0.7 g/liter water) of the planting medium for the first time and continued biweekly at the same rate thereafter. Three-week-old plants were trimmed to 8-cm height, then weekly thereafter to the same height. In microplot experiments, perennial ryegrass was grown in the greenhouse for 6 weeks as described above. Holes in the ground were then made with a cup cutter in an area of established perennial ryegrass turf at the Joseph A. Valentine Turfgrass Research Center, University Park, PA. The pots were then placed in the holes, keeping the rims of the pots at ground level. Fertilization was continued weekly, and grass was mowed to the same 2.5-cm height as the grass surrounding the buried pots until inoculation with *M. oryzae*.

Table 4. Disease incidence for different rates of silicon sources in controlled-environment chamber and microplot experiments

Rate of silicon sources (metric tons/ha)	Disease incidence		
	Trial 1	Trial 2	Trial 3
Controlled-environment experiments			
Peat:sand mix amended with wollastonite			
0.0	71.8	46.1	64.3
0.5	54.9* ^a (24) ^b	34.3* (26)	42.4* (34)
1.0	53.8* (25)	39.0* (15)	30.1* (53)
2.0	44.5* (38)	26.3* (43)	30.8* (52)
5.0	43.2* (40)	23.4* (49)	27.5* (57)
10.0	35.2* (51)	17.9* (61)	23.5* (63)
Peat:sand mix amended with calcium silicate slag			
0.0	72.1	49.8	65.8
0.6	57.9* (20)	27.2* (45)	41.8* (37)
1.2	57.7* (20)	29.2* (41)	42.7* (35)
2.4	53.9* (25)	24.8* (50)	40.7* (38)
6.0	48.3* (33)	20.4* (59)	32.7* (50)
12.0	50.0* (31)	14.5* (71)	31.4* (52)
Hagerstown silt loam amended with wollastonite and calcium silicate slag			
0.0	68.6	42.4	43.6
0.5 wollastonite/0.6 calcium silicate slag	49.8* (28)	27.3* (36)	29.5* (32)
1 wollastonite/1.2 calcium silicate slag	42.8* (38)	25.4* (40)	27.6* (37)
2 wollastonite/2.4 calcium silicate slag	44.3 (35)	25.8* (39)	23.1* (47)
5 wollastonite/6 calcium silicate slag	42.0* (39)	20.1* (53)	19.7* (55)
10 wollastonite/12 calcium silicate slag	42.9* (38)	20.4* (52)	17.5* (60)
Microplot experiments			
Peat:sand mix and Hagerstown silt loam amended with wollastonite and calcium silicate slag			
0.0	76.0	39.1	52.5
0.5 wollastonite/0.6 calcium silicate slag	62.5* (17)	29.0* (26)	46.8* (11)
1.0 wollastonite/1.2 calcium silicate slag	64.0* (15)	27.4* (30)	49.2 (6)
2.0 wollastonite/2.4 calcium silicate slag	58.9* (22)	27.6* (30)	43.5* (17)
5.0 wollastonite/6 calcium silicate slag	56.7* (25)	23.2* (41)	44.5* (15)
10.0 wollastonite/12.0 calcium silicate slag	57.6* (24)	21.8* (44)	41.2* (22)

^a * = significantly ($P \leq 0.05$) lower than the nonamended control for each soil and source combinations in each trial.

^b Percent reduction of disease incidence in each application rate.

Tissue silicon analysis. Grass blades were collected from 9-week-old perennial ryegrass from each replicate of all treatments. The grass blades were dried in a drying oven and ground for analysis of silicon. The silicon content in plant tissue (% by dry weight) was determined by the method described by Elliott and Snyder (20) at the Department of Plant Pathology, Institute of Food and Agricultural Sciences, University of Florida. In this method, 100 mg of plant tissue was mixed with 2 ml of 50% H_2O_2 and 4.5 g of 50% NaOH in a polyethylene tube. These tubes were covered with loose-fitting plastic caps and autoclaved at 138 kPa for 1 h. The contents were then brought to 50 ml with demineralized water. Silicon was extracted by mixing with 35 ml of 20% acetic acid, 10 ml of ammonium molybdate, 5 ml of 20% tartaric acid, and 1 ml of reducing solution (prepared with Na_2SO_3 , 1-amino-2-naphthol-4-sulfonic acid and NaHSO_3). The mixture was allowed to stand for 30 min. Tissue silicon content was then determined by automated colorimetric analysis.

Soil silicon analysis. Soil samples collected from two replicates of each treatment were tested for silicon at the University of Florida, Belle Glade EREC soil testing facility. Soil samples were collected after silicon sources were mixed with the soils and before perennial ryegrass was seeded. Soil silicon levels were determined by the method described by Snyder (39). In this method, silicon from soils was extracted with 0.5 M acetic acid from a 10:25 soil:extractant (vol/vol) mix and determined by a Technicon AutoAnalyzer.

Inoculation of perennial ryegrass plants. An isolate of *M. oryzae* (PA18C-04) was grown on potato dextrose agar plates for 10 days. Agar blocks (approximately 2×2 mm) containing actively growing mycelia were transferred to oatmeal agar plates and grown at 20 to 22°C for 5 days. Sterilized alfalfa stems were placed in the cultures to induce sporulation of the fungus and incubated at 26°C under fluorescent light ($72 \mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) at 12-h day/night cycles for 13 days. The culture plates were flooded with approximately 10 ml of distilled water, and conidia were harvested by scraping the surface of the

plates with a sterilized needle. The conidial suspension was then filtered through four layers of cheesecloth and adjusted to 35×10^3 conidia/ml sterile H_2O . Tween 20 (0.1%) was added to the conidial suspension and mixed well before inoculation. Nine-week-old perennial ryegrass plants were inoculated with the conidial suspension by atomizing the leaves until they were completely wet in both controlled-environment experiments and microplot experiments. Plants atomized with distilled water served as the noninoculated control. After the inoculations in the controlled-environment trials, a polyethylene bag was placed over each inoculated pot to maintain high humidity. The pots were then placed in controlled-environment chambers and maintained at 28°C and continuous fluorescent and incandescent light (77 to $85 \mu\text{E}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). The polyethylene bags were removed after 48 h, and intermittent misting was given every 4 h for 15 min to encourage disease development. The pots were drenched and the grass blades were sprayed with fosetyl-Al (Chipco Signature) at 1 g/liter in order to prevent infection of the plants by *Pythium* species. In microplot

Fig. 1. Relationship between soil silicon level and tissue silicon content of perennial ryegrass grown in peat:sand mix and Hagerstown silt loam amended with wollastonite and calcium silicate slag in controlled-environment experiments (trial 1).

Fig. 2. Relationship between disease incidence and tissue silicon content (transformed to logarithmic values) of perennial ryegrass grown in peat:sand mix and Hagerstown silt loam amended with wollastonite and calcium silicate slag in controlled-environment experiments (trial 1).

experiments, an opaque plastic sheet was placed over the experimental turf area after inoculation in the evening to maintain high humidity in the turf canopy overnight. The plastic sheet was removed the following morning, and this process was repeated between 7 P.M. and 9 A.M. for three consecutive days to encourage conducive conditions for gray leaf spot development. Average ambient temperature and relative humidity during the 2 weeks following inoculation for each trial is shown in Table 2.

Disease assessment and data analysis.

Disease incidence and severity were assessed 2 weeks after inoculation with *M. oryzae* in all trials conducted under both experimental conditions. Disease incidence was assessed by counting symptomatic leaves and total number of blades in each pot and expressed as percent symptomatic leaves for each replicate. Disease severity was assessed on individual blades based on an index that encompasses 10% of the leaf area: 0 = no symptoms; 1 = 1 to 10% of the leaf area necrotic; 2 = 11 to 20% of the leaf area necrotic; 3 = 21 to 30% of the leaf area necrotic; 4 = 31 to 40% of the

leaf area necrotic; 5 = 41 to 50% of the leaf area necrotic; 6 = 51 to 60% of the leaf area necrotic; 7 = 61 to 70% of the leaf area necrotic; 8 = 71 to 80% of the leaf area necrotic; 9 = 81 to 90% of the leaf area necrotic; and 10 = 91 to 100% of the leaf area necrotic. Disease incidence data were analyzed using PROC MIXED procedure of SAS statistical analysis software (SAS Institute, Cary, NC), and significance was determined at $P \leq 0.05$. Least square means were used for pairwise comparisons of treatments. Regression analyses were performed between soil silicon level and tissue silicon content and also between disease incidence and tissue silicon content for each soil and source combination for both experimental conditions. Tissue silicon content was transformed to logarithmic values to remedy departures in error variances and normality in controlled-environment experiments for the regression analysis between tissue silicon content and disease incidence. Disease severity data were analyzed using nonparametric methods developed by Brunner et al. (8) and Shah and Madden

(38) using PROC MIXED procedure of SAS statistical analysis software (SAS).

RESULTS

Effects of silicon on disease incidence.

Disease incidence values varied greatly among the three trials, and the significance of soil effects and the source effects differed among the trials. Disease incidence values from controlled-environment experiments showed that the soil effects were significant ($P \leq 0.05$) for trials 1 and 3 (Table 3). Disease incidence was generally higher in the perennial ryegrass grown in the peat:sand mix than in Hagerstown silt loam in all three trials. As the soil effects were significant for two of the trials, the source effects were analyzed for a soil type to understand the effects of source of silicon on disease incidence within a soil type. The source effects were significant ($P \leq 0.05$) for trials 1 and 3 for peat:sand mix, but were not significant for Hagerstown silt loam in any of the trials. Since there were differences between sources in peat:sand mix, the rate effects were analyzed separately for peat:sand mix

Fig. 3. Relationship between tissue silicon content and soil silicon level of perennial ryegrass grown in peat:sand mix and Hagerstown silt loam amended with wollastonite and calcium silicate slag in microplot experiments (trial 1).

Fig. 4. Relationship between disease incidence and tissue silicon content of perennial ryegrass plants grown in peat:sand mix and Hagerstown silt loam amended with wollastonite and calcium silicate slag in microplot experiments (trial 1).

amended with wollastonite and calcium silicate slag. The rate effects were significant for both soil and source combinations in all three trials. The rate effects analyzed when both sources were combined for Hagerstown silt loam were also significant ($P \leq 0.05$) for all three trials. Disease incidence significantly ($P \leq 0.05$) decreased compared with the nonamended control up to 63, 71, and 60% for peat:sand mix amended with wollastonite, peat:sand mix amended with calcium silicate slag, and Hagerstown silt loam amended with both sources, respectively (Table 4). Regression analysis showed that tissue silicon content consistently increased with increasing amount of silicon in the soils in all four soil and source combinations for all three trials. As shown in Figure 1, linear models best described the relationship between tissue silicon content and the soil silicon level. Regression analysis also showed that disease incidence decreased consistently with increasing tissue silicon content for all four soil and source combinations for all three trials. As shown in Figure 2, linear models best described the relationship between disease incidence and tissue silicon content (transformed to logarithmic values).

In microplot experiments, only the rate effects were consistently significant ($P \leq 0.05$) for all three trials (Table 3). Soil effects and the soil and source interaction effects were significant ($P \leq 0.05$) only for trial 2. Disease incidence significantly ($P \leq 0.05$) decreased compared with the nonamended control up to 44% for soils amended both with wollastonite and with calcium silicate slag (Table 4). Regression analysis showed that tissue silicon content consistently increased with increasing amount of silicon in the soil in all four soil and source combinations for all three trials. As shown in Figure 3, linear models best described the relationship between tissue silicon content and the soil silicon level. Regression analysis also showed that disease incidence decreased consistently with increasing tissue silicon content for all four soil and source combinations for all three trials. As shown in Figure 4, linear and quadratic models best described the relationship between disease incidence and tissue silicon content.

Effects of silicon on disease severity. Analysis of variance-type test statistics from controlled-environment experiments showed that only the rate effects were significant ($P \leq 0.05$) (Table 5) for all three trials. Pairwise comparisons of estimated relative treatment effects showed significant ($P \leq 0.05$) differences between the nonamended control and the treatments amended with silicon in all three trials (Table 6). Analysis of variance-type test statistics from microplot experiments showed that only the rate effects were significant ($P \leq 0.05$) for all three trials (Table 5). The soil and source interaction

effects were significant only for trial 3. Pairwise comparisons of relative treatment effects showed significant ($P \leq 0.05$) differences between the nonamended control and the treatments amended with silicon for all three trials (Table 6).

DISCUSSION

Results from this study are in agreement with the findings from several crop species where silicon amendments have been shown to suppress various diseases (4,10,11,13–15,23,24,29,46,47,49). Gray leaf spot incidence and severity of perennial ryegrass were significantly reduced by silicon applications to both soils in controlled-environment chamber and microplot experiments. Therefore, it appears that at least in these trials, silicon amendments can reduce disease development even in the soils that are not deficient in silicon such as Hagerstown silt loam. Although differences in disease incidence were not consistent between the soil types

under both experimental conditions, disease severity did not differ between the two soil types in any of the trials under both experimental conditions. This suggests that level of disease suppression in both soil types appears to be similar. Differences in disease incidence between the silicon sources were not consistent in peat:sand mix, while disease incidence clearly did not differ between the two sources in Hagerstown silt loam under both experimental conditions. Furthermore, there were no differences in disease severity between the two sources. This suggests that the two silicon sources used in this study were equally effective in reducing disease severity in peat:sand mix and Hagerstown silt loam under both experimental conditions. Several rates of wollastonite and calcium silicate slag applied to soils reduced both disease incidence and severity compared with a nonamended control under both experimental conditions. However, percent reduction of

Table 5. Analysis of variance-type test statistics for the effects of soil type, source, and rate of silicon on gray leaf spot severity in controlled-environment chamber and microplot experiments^a

Effect	dfN	dfD	F	P value
Controlled environment chamber experiments				
Trial 1				
Soil	1.0	4.5	2.6	0.2
Source	1.0	9.7	0.2	0.7
Soil × source	1.0	9.7	0.0	1.0
Rate	3.9	10.4	7.1	0.0
Source × rate	3.9	10.3	0.5	0.8
Soil × source × rate	3.9	10.3	1.6	0.2
Trial 2				
Soil	1.0	2.7	8.7	0.1
Source	1.0	41.5	1.5	0.2
Soil × source	1.0	41.5	0.2	0.7
Rate	4.5	42.2	9.8	<0.0
Source × rate	4.4	40.3	1.1	0.4
Soil × source × rate	4.4	40.3	2.4	0.1
Trial 3				
Soil	1.0	3.6	7.6	0.1
Source	1.0	25.1	2.1	0.2
Soil × source	1.0	25.1	1.3	0.3
Rate	4.3	20.6	8.9	0.0
Source × rate	4.2	20.2	2.1	0.1
Soil × source × rate	4.2	20.2	1.4	0.3
Microplot experiments				
Trial 1				
Soil	1.0	5.7	1.0	0.4
Source	1.0	47.4	0.1	0.8
Soil × source	1.0	47.4	0.3	0.6
Rate	5.0	53.2	4.6	0.0
Source × rate	4.9	50.7	2.0	0.1
Soil × source × rate	4.9	50.7	0.9	0.5
Trial 2				
Soil	1.0	8.4	4.8	0.1
Source	1.0	42.3	1.0	0.3
Soil × source	1.0	42.3	0.2	0.6
Rate	4.4	43.6	5.5	0.0
Source × rate	4.4	43.4	0.6	0.7
Soil × source × rate	4.4	43.4	0.9	0.5
Trial 3				
Soil	1.0	3.6	7.8	0.1
Source	1.0	30.1	0.9	0.3
Soil × source	1.0	30.1	7.0	0.0
Rate	3.7	29.6	10.1	<0.0
Source × rate	3.8	30.2	0.8	0.6
Soil × source × rate	3.8	30.2	0.9	0.5

^a dfN = numerator degrees of freedom; and dfD = denominator degrees of freedom.

Table 6. Median, mean rank, and estimated relative treatment effects of gray leaf spot severity of perennial ryegrass grown in soils amended with different rates of silicon sources in controlled-environment and microplot experiments

Rate of silicon sources (metric tons/ha)	Median disease rating	Mean rank	Estimated relative effect	Lower limit of confidence interval	Upper limit of confidence interval
Controlled-environment chamber experiments					
Trial 1					
0	5.5	70.8	0.8	0.7	0.9
0.5 wollastonite/0.6 calcium silicate slag	3.7	50.1	0.6 ^a	0.5	0.7
1 wollastonite/ 1.2 calcium silicate slag	3.5	39.3	0.5*	0.3	0.6
2 wollastonite/ 2.4 calcium silicate slag	3.1	32.3	0.4*	0.1	0.6
5 wollastonite/6 calcium silicate slag	3.1	36.0	0.4*	0.0	0.8
10 wollastonite/12 calcium silicate slag	3.1	28.0	0.3*	0.1	0.6
Trial 2					
0	5.4	75.2	0.9	0.8	1.0
0.5 wollastonite/ 0.6 calcium silicate slag	4.0	50.7	0.6*	0.4	0.7
1 wollastonite/1.2 calcium silicate slag	3.4	43.8	0.5*	0.4	0.7
2 wollastonite/2.4 calcium silicate slag	3.9	48.6	0.6*	0.4	0.8
5 wollastonite/6 calcium silicate slag	3.2	34.2	0.4*	0.2	0.6
10 wollastonite/12 calcium silicate slag	3.1	34.7	0.4*	0.2	0.5
Trial 3					
0	4.6	67.6	0.8	0.7	0.9
0.5 wollastonite/0.6 calcium silicate slag	3.6	45.8	0.5*	0.4	0.6
1 wollastonite/1.2 calcium silicate slag	3.5	40.7	0.5*	0.2	0.8
2 wollastonite/2.4 calcium silicate slag	3.3	34.9	0.4*	0.2	0.5
5 wollastonite/6 calcium silicate slag	3.4	30.8	0.4*	0.2	0.5
10 wollastonite/12 calcium silicate slag	3.3	28.6	0.3*	0.2	0.4
Microplot experiments					
Trial 1					
0	3.6	71.0	0.8	0.6	1.0
0.5 wollastonite/0.6 calcium silicate slag	3.0	51.2	0.6*	0.4	0.8
1 wollastonite/1.2 calcium silicate slag	3.0	48.9	0.6*	0.4	0.8
2 wollastonite/2.4 calcium silicate slag	2.8	39.8	0.5*	0.2	0.7
5 wollastonite/6 calcium silicate slag	2.9	42.8	0.5*	0.3	0.7
10 wollastonite/12 calcium silicate slag	2.7	37.4	0.4*	0.2	0.6
Trial 2					
0	5.2	76.0	0.9	0.8	1.0
0.5 wollastonite/0.6 calcium silicate slag	4.6	41.1	0.5*	0.4	0.6
1 wollastonite/1.2 calcium silicate slag	4.5	42.2	0.5*	0.3	0.7
2 wollastonite/2.4 calcium silicate slag	4.5	48.2	0.6*	0.4	0.7
5 wollastonite/6 calcium silicate slag	4.1	41.6	0.5*	0.3	0.7
10 wollastonite/12 calcium silicate slag	4.1	35.1	0.4*	0.2	0.6
Trial 3					
0	5.1	74.7	0.9	0.8	1.0
0.5 wollastonite/0.6 calcium silicate slag	4.5	49.9	0.6*	0.5	0.7
1 wollastonite/1.2 calcium silicate slag	4.4	44.6	0.5*	0.4	0.7
2 wollastonite/2.4 calcium silicate slag	4.4	45.1	0.5*	0.4	0.7
5 wollastonite/6 calcium silicate slag	4.4	45.1	0.5*	0.3	0.8
10 wollastonite/12 calcium silicate slag	3.9	25.3	0.3*	0.2	0.4

^a * = indicates the relative effects were significantly ($P \leq 0.05$) different from the nonamended control.

gray leaf spot incidence was relatively less in microplot experiments than that in the controlled-environment experiments.

Silicon amendments have been reported to reduce the rate of a disease epidemic by affecting several components of resistance in blast disease of rice and gray leaf spot of St. Augustinegrass (7,37,47). Seebold et al. (37) quantified the effects of silicon on several components of resistance to rice blast on four cultivars of rice with differential susceptibilities to race IB-49 of *M. oryzae* and provided clear evidence that increasing rate of silicon delayed disease onset and reduced the number of sporulating lesions, size and rate of lesion expansion, necrotic leaf area, and the number of spores per lesion in each cultivar. However, Brecht et al. (7) showed that lesion number was the only component of resistance affected for gray leaf spot development on St. Augustinegrass, reducing the number of lesions between 26 and 61%

when silicon treatments are compared with the nontreated control. In our study, disease severity was significantly reduced in silicon-amended treatments compared with the nonamended control. However, this study did not evaluate the effects of silicon on other components of resistance. Future studies may be conducted to determine the effects of silicon on components of resistance in the gray leaf spot-perennial ryegrass pathosystem.

This study investigated the effects of preplanting silicon applications on a single cultivar of perennial ryegrass. However, most golf course fairways and roughs have different blends of perennial ryegrass cultivars. There may be a genotypic variation in silicon accumulation and disease resistance among the cultivars of perennial ryegrass as reported in rice (18) and St. Augustinegrass (13). In addition, established perennial ryegrass stands on golf courses that are managed as fairways and

roughs may differ in their response to soil amendments with silicon, since mowing height and frequency vary in these areas. In the present study, the differences in mowing height after the grass pots were buried may have contributed to the lower levels of disease suppression observed in the microplot experiments. Therefore, further studies are warranted to evaluate the effects of silicon applications on gray leaf spot development in perennial ryegrass turf in golf courses employing standard cultural management practices.

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