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RESEARCH

Nitrogen and Iron Sulfate Affect Microdochium Patch Severity and Turf Quality on Annual Bluegrass Putting Greens

Clint M. Mattox,* Alec R. Kowalewski, Brian W. McDonald, John G. Lambrinos, Brian L. Daviscourt, and Jay W. Pscheidt

ABSTRACT

Microdochium patch is an important turfgrass disease in cool-humid regions and is caused by the pathogen *Microdochium nivale* (Fries) Samuels & Hallett. Control of the pathogen is necessary to provide acceptable putting-green-quality turf, and fungicide applications are the predominant method of control. Increasing pesticide restrictions have generated interest in alternative management techniques of Microdochium patch. This research evaluated the effects of three nitrogen and five iron sulfate rates on Microdochium patch development on a trafficked, sand-based, annual bluegrass (*Poa annua* L.) putting green in Corvallis, OR for over 2 yr in the absence of fungicides. Data included turf quality, area under disease progress curve, and soil test results of saturated paste extract pH, cation extractable sulfate, and DTPA-sorbitol extractable iron. This research provided evidence that low rates of urea (4.88 kg N ha^{-1}) applied every 2 wk did not lead to an increase in Microdochium patch severity and that iron sulfate applications decreased Microdochium patch on annual bluegrass putting greens. Despite the disease suppression observed, no treatment received a turf-quality rating considered acceptable. Low turf-quality ratings where disease development was low were attributed to turfgrass thinning or blackening of the shoots resulting from iron sulfate applications. Soil tests provided evidence that the highest iron sulfate level used in this study (97.65 kg ha^{-1}) applied every 2 wk would likely lead to a lower soil pH and an increase in soil sulfate levels.

C.M. Mattox, A.R. Kowalewski, B.W. McDonald, J.G. Lambrinos, and B.L. Daviscourt, Dep. of Horticulture, 4017 Agricultural and Life Sciences Building, Oregon State Univ., Corvallis, OR 97331; J.W. Pscheidt Dep. of Botany and Plant Pathology, 1089 Cordley Hall, Oregon State Univ., Corvallis, OR 97331. Received 24 Feb. 2016. Accepted 28 July 2016. *Corresponding author (Clint.Mattox@oregonstate.edu). Assigned to Associate Editor Douglas Soldat.

Abbreviations: AUDPC, area under disease control progress curve.

Microdochium patch is a turfgrass disease caused by the fungal pathogen *Microdochium nivale* (Fries) Samuels & Hallett and is most active in the field when temperatures are between 8 and 17°C and when there are more than 20 h of ≥90% humidity (Dwyer, 2004). These conditions are common in the Pacific Northwest and northern Europe, where Microdochium patch is one of the most prominent turfgrass diseases (Vargas, 2005). Fungicide applications are currently the predominant method of control for Microdochium patch; however, increasing pesticide restrictions in North America and Europe (Ministère de l'agriculture et de la pêche, 2006; Christie, 2010) are causing turfgrass managers to look for alternative ways of managing this disease.

Microdochium patch severity has often been linked with turfgrass nutrition. High levels of nitrogen (N) fertility have been associated with an increase in susceptibility of turfgrass to Microdochium patch, referring to N's impact on leaf succulence, although no guidelines are provided as to how much constitutes a high level (Smiley et al., 2005). Early studies showed that Microdochium patch severity increased as a result of higher annual N applications on both annual bluegrass (*Poa annua* L.) and colonial bentgrass (*Agrostis tenuis* Sibth.) (Sports Turf Bulletin, 1956; Brauen et al., 1975). However, there is little, if any, peer reviewed research investigating how low rates of N (e.g., 4.88 and 9.76 kg N ha^{-1} 2 wk^{-1}), applied during the late fall and winter periods, affect

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Microdochium patch activity and turfgrass recuperation resulting from golfer traffic in the absence of fungicides.

Soil pH is often reported to have an effect on Microdochium patch severity with higher pH considered conducive to disease (Smith, 1958; Couch, 1995; Smiley et al., 2005). A study on colonial bentgrass in Puyallup, WA, showed that 224 kg of sulfur ha^{-1} annually resulted in complete control of Microdochium patch (Brauen et al., 1975). Unlike sulfur (S), which requires microorganisms for oxidation to occur (and is therefore temperature dependent) (McCarty et al., 2003), iron sulfate ($FeSO_4$) reacts readily with water to release hydrogen ions, resulting in a reduction of soil pH (Carrow et al., 2001). The use of $FeSO_4$ to manage Microdochium patch is a common practice in Europe (Baldwin, 1989; Mabbett, 2014; Pitchcare, 2015) and has also been shown to reduce dollar spot (*Sclerotinia homeocarpa* Bennett) severity in Virginia (Reams, 2013). With the exception of a 1-yr study in the United Kingdom on a mixed stand of turfgrass where a decrease in Microdochium patch severity was observed due to $FeSO_4$ additions (Oostendorp, 2012), little research exists that quantifies the effects of $FeSO_4$ applications on the severity of Microdochium patch.

The objective of this study was to quantify the effects of $FeSO_4$ and urea application rates on the severity of Microdochium patch on an annual bluegrass putting green, as well as turf quality affected by simulated golfer traffic in the absence of fungicide applications.

MATERIALS AND METHODS

Experimental Design

The experiment was conducted at the Oregon State University Lewis–Brown Horticulture Farm in Corvallis, OR, on a putting green constructed by placing 15 cm of USGA-recommended particle-size sand (USGA, 2004) directly on the native McBee silty clay loam (fine-silty, mixed, superactive, mesic Aquic Cumulic Haploxerolls) (UC Davis, 2015). Annual bluegrass was established by using aerification cores from an annual bluegrass putting green with USGA sand at a local country club in Corvallis, OR. The experimental design was a 3- by 5-factorial treatment structure arranged in a randomized complete block design with four replications. The trial was repeated over 2 yr. Individual plots were 1.5 m^2, and the total experimental area was 90 m^2. Factors included three urea (46 N–0 P–0 K) rates (0.0, 4.88, and 9.76 kg N ha^{-1}) and five $FeSO_4$ heptahydrate (11.5% S and 20.1% Fe) rates (0.0, 12.21, 24.41, 48.82, and 97.65 kg product ha^{-1}). Urea rates of 4.88 and 9.76 kg N ha^{-1} reflect N applications typically applied to golf greens in a spoon-feeding fertilization program (Christians, 2007). Due to yearlong growth, annual N fertility programs for annual bluegrass putting greens in Oregon range from 159 to 317 kg N ha^{-1} (Golembiewski et al., 2009). A range of $FeSO_4$ rates was used to determine rates that might have an effect on Microdochium patch severity. Treatments were applied every 2 wk from 26 Sept. 2013 to 15 Apr. 2014 and again from 22 Sept. 2014 to 15 Apr. 2015. All treatments were applied with a CO_2–pressurized backpack sprayer with a four-nozzle (25.4 cm of nozzle spacing) handheld boom equipped with four XR80015 nozzles using a pressure of 280 kPa at the boom. Carrier volume was 814 L ha^{-1} and walking speed was calibrated with a metronome. To simulate golf conditions similar to those of a municipal course in Corvallis, OR, golfer traffic representing 76 rounds of golf per day was performed by walking over the plots using golf shoes, following the protocol set out by Hathaway and Nikolai (2005).

Turfgrass Maintenance

The green was mowed once wk^{-1} in November through March and five times wk^{-1} for the rest of the year, at a mowing height of 3.8 mm with clippings removed. Preceding the first year of the trial, 234 kg N ha^{-1} was applied from April to the beginning of the trial using a quick release compound fertilizer containing 23.7% urea N and 4.3% nitrate N (28 N–2.2 P–15 K) (Andersons 28–5–18, Maumee, OH) to establish the green. The August applications of this fertilizer consisted of 9.8 kg N ha^{-1}, applied on 2, 16, and 29 Aug. 2013. Urea was applied on 5 and 20 Sept. 2013 at a rate of 9.8 kg N ha^{-1}. Between the two trial years, 80 kg N ha^{-1} was used to recover the green from the damage of the first year. The same Andersons 28–5–18 fertilizer was applied at a rate of 9.8 kg N ha^{-1} on 8 and 22 Aug. 2014, as well as on 5 Sept. 2014. A 9.8-kg N ha^{-1} application of urea was made on 19 September. Sand topdressing was applied at a rate of 2.7 L m^{-2} every 2 wk from 5 July to 5 Sept. 2013, and again from 3 July to 2 Sept. 2014. Hollow-tine aerification using 13-mm diameter tines on 5.1- by 5.1-cm spacing at a 76-mm depth was performed on 18 Sept. 2013, and again on 19 June and 16 Sept. 2014. No fungicide treatments were applied throughout the study. Fungicides were applied as a prophylactic against Anthracnose (*Colletotrichum cereale* Manns) and dollar spot in each summer before the trials started. During the trial period, no irrigation was applied due to the cool-humid conditions in the Willamette Valley. During the summer, irrigation was applied using well water with a pH of 6.3. Irrigation was set to replace 50% of the evapotranspiration every day, and the green was hand watered to avoid drought stress; peak rates during summer heat stress resulted in 2.4 cm of water being applied per week.

Response Variables

Response variables included area under disease progress curve (AUDPC), turf quality, saturated paste extract pH, DTPA-sorbitol extractable Fe, and cation extractable sulfate levels.

Area under disease progress curve data were calculated using disease severity data quantified by stratified sampling that were collected monthly after the initial data collection (26 Sept. 2013 and 22 Sept. 2014) up to the date of peak disease (25 Feb. 2014 and 16 Feb. 2015) (Tables 1 and 2). The stratified sampling data was obtained from digital images, two subsamples per plot, collected each month 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 50-point grid was overlaid on each image and grid counts of Microdochium patch severity were recorded for the photo box images (Laycock and Canaway, 1980; Richardson et al., 2001). An area

Table 1. Percent disease by treatment over time on an annual bluegrass putting green, as influenced by N and $FeSO_4$ treatments in Corvallis, OR.

		Year one†							
		2013				2014			
N rate	$FeSO_4$ rate	26 Sept.	23 Oct.	20 Nov.	19 Dec.	16 Jan.	25 Feb.	21 Mar.	15 Apr.
—— kg ha^{-1} 2 wk^{-1} ——		%							
0.0	0.0	0.0‡	0.0	22.5	35.3	65.0	79.5	75.3	58.3
0.0	12.2	0.0	0.0	12.0	25.0	49.8	59.5	58.3	49.8
0.0	24.4	0.0	0.0	17.0	29.0	46.8	49.8	41.8	29.5
0.0	48.8	0.0	0.0	2.3	3.3	5.5	3.8	8.0	8.3
0.0	97.7	0.0	0.0	0.0	0.0	0.5	0.5	1.3	0.5
4.9	0.0	0.0	0.0	10.8	19.8	52.0	62.3	37.8	19.5
4.9	12.2	0.0	0.0	17.5	29.3	50.5	47.8	27.0	17.5
4.9	24.4	0.0	0.0	8.8	18.5	38.3	37.3	15.3	8.3
4.9	48.8	0.0	0.0	15.0	20.3	29.5	24.0	15.5	6.0
4.9	97.7	0.0	0.0	0.5	0.5	1.5	1.3	1.3	0.0
9.8	0.0	0.0	0.0	19.0	33.0	62.8	62.5	27.3	14.8
9.8	12.2	0.0	0.0	30.8	43.3	69.8	62.0	25.5	12.8
9.8	24.4	0.0	0.0	14.8	26.3	55.5	47.0	18.0	7.3
9.8	48.8	0.0	0.0	18.0	27.5	49.3	48.0	15.8	8.5
9.8	97.7	0.0	0.0	3.8	6.0	10.8	6.5	5.8	1.5

† Trial began on 26 Sept. 2013 and concluded on 15 Apr. 2014.

‡ Percent disease as determined by stratified sampling.

Table 2. Percent disease by treatment over time on an annual bluegrass putting green, as influenced by N and $FeSO_4$ treatments in Corvallis, OR.

		Year two†							
		2014				2015			
N rate	$FeSO_4$ rate	22 Sept.	16 Oct.	17 Nov.	18 Dec.	13 Jan.	16 Feb.	17 Mar.	15 Apr.
—— kg ha^{-1} 2 wk^{-1} ——		%							
0.0	0.0	0.0‡	0.0	1.3	7.3	25.3	51.5	48.8	42.8
0.0	12.2	0.0	0.0	0.5	3.0	5.3	14.5	16.3	21.8
0.0	24.4	0.0	0.5	3.5	7.8	10.0	16.0	15.8	14.3
0.0	48.8	0.0	0.0	0.0	2.5	0.5	1.5	1.5	1.3
0.0	97.7	0.0	0.3	0.5	1.0	0.5	0.0	0.0	0.8
4.9	0.0	0.0	0.0	0.3	3.3	11.5	36.3	31.0	15.5
4.9	12.2	0.0	0.0	0.3	2.0	7.5	19.5	14.3	6.8
4.9	24.4	0.0	0.0	0.5	1.0	3.3	10.8	10.3	6.0
4.9	48.8	0.0	0.5	0.3	1.8	2.5	4.3	3.0	3.0
4.9	97.7	0.0	0.0	0.8	2.0	0.8	0.8	0.5	0.3
9.8	0.0	0.0	0.0	1.3	7.3	25.0	41.3	32.0	13.3
9.8	12.2	0.0	0.3	2.3	10.0	29.5	34.0	26.8	8.3
9.8	24.4	0.0	0.0	0.3	4.5	13.5	22.3	23.5	8.8
9.8	48.8	0.0	0.8	3.0	6.5	15.3	24.8	21.8	6.8
9.8	97.7	0.0	0.8	2.0	7.5	8.0	8.5	11.5	5.3

† Trial began on 22 Sept. 2014 and concluded on 15 Apr. 2015.

‡ Percent disease as determined by stratified sampling.

under disease progress curve was calculated by taking the sum (Σ) of the average disease severity $[(y^i + y^{i+1})/2]$ between two observations (y^i) multiplied by the time interval between the observations $[t^{i+1} - t^i]$ using the formula $\Sigma[(y^i + y^{i+1})/2](t^{i+1} - t^i)$, as determined by Shaner and Finney (1977). It was decided to calculate up to the peak of disease only, because following this date, the plots no longer receiving N recuperated much more slowly than plots receiving N treatments and therefore would receive higher AUDPC values, not because of a continuously high level of disease severity, but because of a lack of recuperation due to less N additions.

Turf quality ratings were assigned using the National Turfgrass Evaluation Program (NTEP) rating system (Morris and Shearman, 2015) at the peak of disease in February of 2014 and 2015. Turf quality ratings were determined by the amalgamation of five influences: color, density, uniformity, texture, and damage due to stress or disease. Turf quality ratings used a one-to-nine scale, with a one rating given to dead turf, a nine given to ideal turf, and a rating of six or higher being considered acceptable for putting green turf (Morris and Shearman, 2015).

Soil samples were collected on 17 May 2014 and 18 May 2015. Twenty-five samples from each plot were collected to a depth of 76 mm using a soil core sampler, 16 mm in diameter. The top 12 mm was removed to separate the thatch from the soil collected. The samples were mixed, placed in plastic bags and sent to a soil-testing lab (A and L Labs, Modesto, CA) for analysis of saturated paste extract pH, DTPA-sorbitol extractable Fe, and cation extractable sulfate levels, according to reference methods for the western United States (Gavlak et al., 2005). To analyze pH, a saturated paste extraction was prepared with deionized water. The DTPA-sorbitol extraction of Fe was prepared with a 0.005 M DTPA-sorbitol extraction solution. Cation extractable sulfate levels were extracted with an ammonium-acetate extraction.

Statistical Analysis

Using Levene's test, it was determined that the AUDPC data did not meet the assumption of homoscedasticity; therefore, the data were transformed using arcsine transformation and were subjected to analysis of variance using R 3.3.0 (R Core Team, 2016). Data presented were back-transformed to the original scale for the construction of means tables and figures. Factors within this analysis included urea rate and $FeSO_4$ rate. When main effects and interactions were significant, Fisher's Least Significant Difference (LSD) was used to separate individual means at a 0.05 level of probability. Visual quality data are nonparametric; therefore, the Kruskal–Wallis one-way analysis of variance was performed in R 3.3.0 (R Core Team, 2016) to determine if any of the samples were stochastically dominant. The R package PMCMR (Pohlert, 2014) was used to separate the individual means using Dunn's test at a 0.05 level of probability.

RESULTS AND DISCUSSION

Area under disease progress curve analysis for year one resulted in a significant interaction between the N and $FeSO_4$ applications because Microdochium patch severity was not consistent across all N rates in regards to the $FeSO_4$ combinations (Table 3 and Fig. 1). In particular, the three N treatments, in combination with either the 48.82- or 97.65-kg $FeSO_4$ rate, showed significant separation using LSD (α 0.05), compared with the other N and $FeSO_4$ combinations (Fig. 1). The AUDPC data for year one suggests that urea applications, in combination with the lower levels of $FeSO_4$ (0.0, 12.21, or 24.42 kg $FeSO_4$) included in this study, had only limited effects on Microdochium patch severity. When the 48.82-kg $FeSO_4$ level was used, Microdochium patch severity was greater in plots receiving urea compared with plots not receiving any urea, suggesting that annual bluegrass receiving urea was more susceptible to Microdochium patch than plots not receiving urea at this $FeSO_4$ rate. At the 97.65-kg $FeSO_4$ level, the lowest level of urea (4.88 kg N ha^{-1}) did not lead to an increase in Microdochium patch compared with plots not receiving urea. The highest level of urea (9.65 kg N ha^{-1}) resulted in the most Microdochium patch severity at this level of $FeSO_4$.

Table 3. Analysis of variance and main effects for area under disease progress curve (AUDPC), percent Microdochium patch (*M. nivale*), turf quality, soil-test saturated paste extract pH (pH), cation extractable sulfate (S), and DTPA-sorbitol extractable iron (Fe) on an annual bluegrass putting green, as influenced by N and $FeSO_4$ treatments in Corvallis, OR.

		Year one†			
	df	AUDPC‡	pH	S	Fe
Source of variation		——— Pr > F§ ———			
N	2	***	*	ns	**
$FeSO_4$	4	***	ns	**	ns
N × $FeSO_4$	8	*	ns	ns	ns
N rate¶				——— ppm ———	
0.00			5.8 b#	13.2 ns	53.9 a
4.88			5.8 ab	11.1 ns	47.5 b
9.76			5.9 a	10.7 ns	46.2 b
SED			0.037	1.363	2.269
$FeSO_4$ rate					
00.00			5.8 ns	9.2 b	49.2 ns
12.21			5.8 ns	10.3 b	47.8 ns
24.41			5.8 ns	11.0 b	47.3 ns
48.82			5.8 ns	11.4 b	50.3 ns
97.65			5.8 ns	16.4 a	51.3 ns
SED			0.048	1.760	2.929

* Significant at the 0.05 level; ** significant at the 0.01 level; *** significant at the 0.001 level; ns, not significant.

† Trial began on 26 Sept. 2013 and concluded on 15 Apr. 2014.

‡ Calculated from the beginning of the year one trial (26 Sept. 2013) until the peak of disease (25 Feb. 2014). Disease severity was quantified using stratified sampling on each collection date.

§ Where Pr is the probability of observing an F statistic that is at least as extreme as the one observed given that the null hypothesis is true, and F is the ratio of the group mean variance to the mean of the within-group variances.

¶ Rates for N and $FeSO_4$ are given in kg ha^{-1} applied every 2 wk; SED, standard error of the difference.

Means in the same column followed by the same letter are not significantly different according to Fisher's protected least significant difference ($P \leq 0.05$).

The interaction analysis for AUDPC in year one revealed that Microdochium patch severity decreased as $FeSO_4$ levels increased, although the magnitude of the decrease was not the same among all urea levels (Fig. 1). A sharp decrease in disease severity was observed when 48.82 kg $FeSO_4$ was applied in the absence of urea, while the same level of $FeSO_4$, in combination with the other urea levels, did not result in the same magnitude of disease reduction. The highest level of $FeSO_4$ (97.65 kg $FeSO_4$ ha^{-1}) included in this study resulted in a decrease in disease among all urea levels. The greatest disease suppression in year one was observed when 48.82 kg $FeSO_4$ ha^{-1} was applied every 2 wk in the absence of urea, or when 97.65 kg $FeSO_4$ ha^{-1} was applied in the absence of urea or in the combination with urea applied at 4.88 kg N ha^{-1} every 2 wk.

Area under disease progress curve data for year two revealed that a low rate of urea (4.88 kg N ha^{-1}) applied every 2 wk during the winter period did not increase disease development compared with plots not receiving any

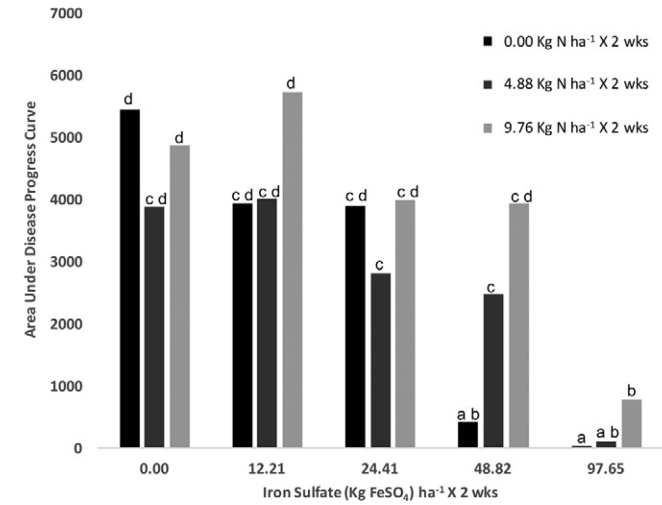

Fig. 1. Effects of N and $FeSO_4$ on area under disease progress curve calculated from 26 Sept. 2013 to 25 Feb. 2014 on an annual bluegrass putting green in Corvallis, OR. Nitrogen (0.00, 4.88, and 9.76 kg N ha^{-1}) and $FeSO_4$ (0.00, 12.21, 24.41, 48.82, and 97.65 kg $FeSO_4$ ha^{-1}) were applied every 2 wk. Means denoted with the same letter are not significantly different according to Fisher's protected least significant difference test at $P \leq 0.05$.

urea (Table 4). The highest level of urea used in year two of this study (9.76 kg N ha^{-1}) did result in a greater level of Microdochium patch severity. Linear regression analysis of the AUDPC data did not identify a correlation between N rate and disease in year two ($r^2 = 0.0725$) of this study. In year two, AUDPC data showed that, as rates of $FeSO_4$ increased, Microdochium patch severity decreased (Table 4). Treatments in the absence of $FeSO_4$ produced the highest AUDPC results (1546) compared with the 97.65-kg $FeSO_4$ rate that produced an AUDPC value of 288. Linear regression analysis identified a weak negative correlation between $FeSO_4$ rate and AUDPC for year two ($r^2 = 0.1975$) of the study.

Many turfgrass disease books, publications, or resources refer to the risk of winter N fertilization applications associated with Microdochium patch severity (Couch 1995; Smiley et al., 2005; Vargas, 2005). Early research showed that ammonium sulfate additions of 214 kg N ha^{-1} to annual bluegrass turf in the summer resulted in 31% Microdochium patch observed the following spring compared with 0% in plots not receiving N (Sports Turf Bulletin, 1956). However, other research showed a decrease in Microdochium patch on colonial bentgrass greens as February to December urea applications levels increased from 293 to 586 and 976 kg N ha^{-1} in the absence of sulfur additions (Brauen et al., 1975). In contrast to the study on colonial bentgrass, in the current study, there is suggestion that biweekly applications of 9.76 kg N ha^{-1} increased Microdochium patch compared with the 4.88-kg N ha^{-1} rate; however, this current study also suggests that a 4.88-kg N ha^{-1} rate every 2 wk does not increase Microdochium patch compared with no N additions. These results can be especially useful in climates conducive to winter growth, such as in the Pacific Northwest, where annual bluegrass could benefit from low biweekly rates of urea (4.88 kg N ha^{-1}) without increasing Microdochium patch severity. While the increase in N from 0 to 4.88 kg N ha^{-1} every 2 wk likely leads to greater turfgrass recuperation (Beard, 1973), the higher rate of 9.76 kg N ha^{-1} may lead to greater turfgrass succulence (Danneberger, 2009) and a higher risk of Microdochium patch severity.

Iron sulfate applications leading to a reduction in Microdochium patch severity was previously reported by Oostendorp (2012), where a 1-yr experiment on three golf course putting greens in the United Kingdom consisting of a mixed stand of turf (*A. tenuis.*, *P. annua*, and *Festuca rubra* L. subspecies *commutata*) received 10 kg $FeSO_4$ ha^{-1} every 5 wk for 7 mo. Oostendorp found an average 58% reduction in Microdochium patch severity on areas receiving the $FeSO_4$ treatments compared with plots not

Table 4. Analysis of variance and main effects of area under disease progress curve (AUDPC), percent Microdochium patch (*M. nivale*), turf quality, soil-test saturated paste extract pH (pH), cation extractable sulfate (S), and DTPA-sorbitol extractable iron (Fe) on an annual bluegrass putting green, as influenced by N and $FeSO_4$ treatments in Corvallis, OR.

		Year two†			
	df	AUDPC‡	pH	S	Fe
Source of Variation		Pr > F§			
N	2	***	ns	ns	ns
$FeSO_4$	4	***	*	***	ns
N × $FeSO_4$	8	ns	ns	ns	ns
N rate¶				ppm	
0.00		696 b#	5.6 ns	13.0 ns	67.9 ns
4.88		469 b	5.6 ns	10.7 ns	64.0 ns
9.76		1261 a	5.6 ns	10.5 ns	66.8 ns
SED			0.040	1.183	2.611
$FeSO_4$ rate					
00.00		1546 a	5.7 a	6.4 d	65.3 ns
12.21		984 b	5.6 a	7.4 cd	66.6 ns
24.41		720 bc	5.7 a	10.1 bc	61.4 ns
48.82		503 cd	5.6 ab	12.1 b	67.4 ns
97.65		288 d	5.5 b	21.0 a	70.5 ns
SED			0.051	1.528	3.371

* Significant at the 0.05 level; ** significant at the 0.01 level; *** significant at the 0.001 level; ns, not significant.

† Trial began on 22 Sept. 2014 and concluded on 15 Apr. 2015.

‡ Calculated from the beginning of the year two trial (22 Sept. 2014) until the peak of disease (16 Feb. 2015). Disease severity was quantified using stratified sampling on each collection date.

§ Where Pr is the probability of observing an F statistic that is at least as extreme as the one observed given that the null hypothesis is true, and F is the ratio of the group mean variance to the mean of the within-group variances.

¶ Rates for N and $FeSO_4$ are given in kg ha^{-1} applied every 2 wk; SED, standard error of the difference.

\# Means in the same column followed by the same letter are not significantly different according to Fisher's protected least significant difference ($P \leq 0.05$).

receiving any $FeSO_4$. In a different study, biweekly applications of $FeSO_4$ at a rate of 48.8 kg ha^{-1} over 6 mo in the summer led to less dollar spot on a study on creeping bentgrass (Reams, 2013). The reason for disease reduction is unclear, however possible explanations are that $FeSO_4$ is decreasing the pH (Carrow et al., 2001) thus causing the environment to be less conducive to disease (Smith, 1958), Fe toxicity might be responsible (Forsyth, 1957; Reams, 2013) or hardening of the leaves might be causing the leaves to become less succulent and less susceptible to disease (Cole, 1930; Danneberger, 2009; Watson, 2008).

While some $FeSO_4$ treatments in this study resulted in a decrease in disease severity, turf quality was observed to be unacceptable on all treatments during both years of the study. Significant differences between the treatments was observed using the Kruskal–Wallis test for year one ($P < 0.01$) and year two ($P < 0.01$). Treatments of 4.88 kg N ha^{-1}, in combination with 97.65 kg $FeSO_4$ ha^{-1} every 2 wk, was in the group with the highest turf quality over both years; however, the mean turf quality for this treatment combination in both years was less than 5.0. Treatments receiving no N in combination with 97.65 kg $FeSO_4$ ha^{-1} every 2 wk resulted in the lowest turf quality during both years of the study (Fig. 2 and 3).

The primary factor responsible for decreasing turf quality on plots with no disease was loss of turf density likely due to foliar toxicity (Wehner, 1992; Yust et al., 1984). It has been reported that on most turfgrasses, rates up to 5.6 kg Fe ha^{-1} will not result in foliar burn (Carrow et al., 2001), although Yust et al. (1984) reported no injury up to the 17.7-kg Fe ha^{-1} rate. Experiments in the greenhouse have shown that Fe applications at rates as low as 7.6 kg Fe ha^{-1} reduced annual bluegrass shoot growth (Xu and Mancino 2001). Field studies on Kentucky bluegrass (*Poa pratensis* L.) have shown that Fe phytotoxicity occurs with applications above 17.7 kg Fe ha^{-1} (Yust et al., 1984). Reams (2013) also observed that high rates of $FeSO_4$ (48.8 kg ha^{-1} 2 wk^{-1}) resulted in a reduction of annual bluegrass populations. This could explain the loss of turf density observed in our study where Fe applications ranged from 10.9 to 19.5 kg Fe ha^{-1} 2 wk^{-1}.

Another factor leading to a decrease in turf quality was unacceptable turfgrass color. The highest rate of $FeSO_4$ (97.65 Kg $FeSO_4$ ha^{-1}) used in this study corresponded to a rate of 19.5 Kg Fe ha^{-1} and decreased disease to acceptable levels. However, the aforementioned treatment also caused blackening of the turfgrass, which was further aggravated on treatments not receiving N additions. Kussow (1995) found a similar color benefit from N where two summer applications of compound N and Fe fertilizers with rates ranging from 4.88 to 67.34 Kg N ha^{-1} and 0 to 58.56 Kg Fe ha^{-1} were applied to creeping bentgrass (*Agrostis stolonifera* L.). In those plots, N accounted for 94% of the variation in bentgrass color. The water-carrier volume in this trial was set at 814 L h^{-1} to mimic volumes commonly used by turfgrass professionals for fungicide applications of foliar diseases (Latin, 2011). A larger carrier volume might decrease the blackening effect caused by the $FeSO_4$ additions.

Soil tests provide some insight into long-term effects on soil nutrient levels, and particularly on soil acidity and sulfate levels. At the end of the first year of the study, saturated paste extract pH was higher in plots receiving the highest rate of N (9.76 kg N ha^{-1}) additions in the form

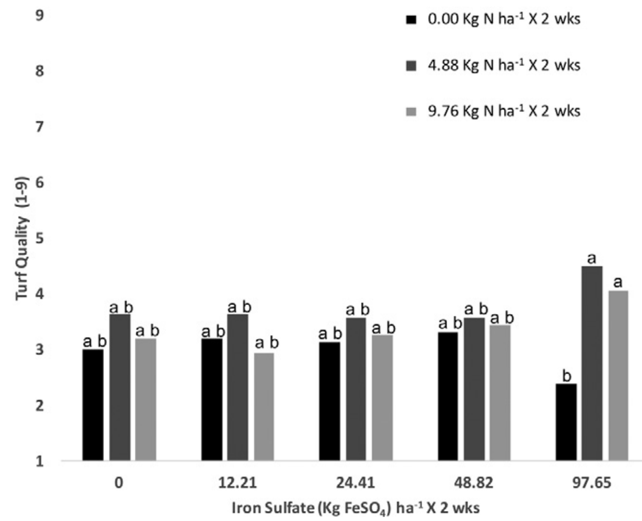

Fig. 2. Effects of N and $FeSO_4$ on turf quality ratings on an annual bluegrass putting green in Corvallis, OR, on 25 Feb. 2014. Nitrogen (0.00, 4.88, and 9.76 kg N ha^{-1}) and $FeSO_4$ (0.00, 12.21, 24.41, 48.82, and 97.65 kg $FeSO_4$ ha^{-1}) were applied every 2 wk. Means denoted with the same letter are not significantly different according to Dunn's all-pairwise comparisons test at $P \leq 0.05$.

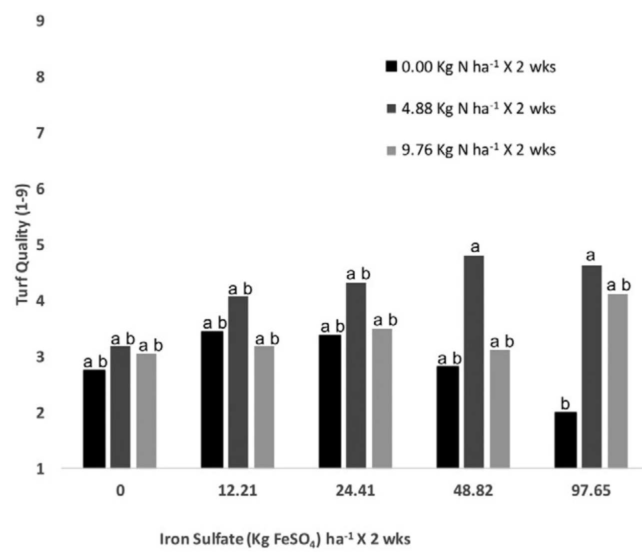

Fig. 3. Effects of N and $FeSO_4$ on turf quality ratings on an annual bluegrass putting green in Corvallis, OR, on 16 Feb. 2015. Nitrogen (0.00, 4.88, and 9.76 kg N ha^{-1}) and $FeSO_4$ (0.00, 12.21, 24.41, 48.82, and 97.65 kg $FeSO_4$ ha^{-1}) were applied every 2 wk. Means denoted with the same letter are not significantly different according to Dunn's all-pairwise comparisons test at $P \leq 0.05$.

of urea (Table 3). This is surprising, as urea is known to contribute to soil acidity (Goss et al., 1977; Schroder et al., 2011). However, this result was only observed in the first year of the study, and the difference between the lowest average saturated paste extract pH observed (5.75) and the highest (5.85) does not likely provide any practical impact, from the turfgrass manager's perspective.

Even though $FeSO_4$ additions did not affect saturated paste extract pH in the first year of the study, differences were observed in year two, with the highest $FeSO_4$ rates (97.65 kg $FeSO_4$ ha^{-1}) resulting in the lowest saturated paste extract pH (Table 4).

A significant difference was also observed in the amount of cation extractable sulfate in the plots treated with different rates of $FeSO_4$ during year one and year two (Tables 3 and 4), with the 97.65-kg $FeSO_4$ ha^{-1} rate resulting in significantly higher cation extractable sulfate soil-test levels compared with the other $FeSO_4$ rates in both years. A significant difference in DTPA-sorbitol extractable Fe levels among the N treatments was only observed the first year, where treatments not receiving N resulted in the highest levels of extractable Fe (Table 3).

CONCLUSIONS

There is strong evidence that a low rate of N (4.88 kg N ha^{-1}) applied every 2 wk in the form of urea on annual bluegrass putting greens during the winter period does not increase Microdochium patch severity. Therefore, turfgrass managers could use low N applications to assist annual bluegrass wear tolerance and recuperation from golfer traffic during the winter months on putting greens in the Pacific Northwest without adversely affecting the risk of Microdochium patch. There is also strong evidence that, as rates of $FeSO_4$ applications increase, Microdochium patch severity decreases on annual bluegrass putting greens. When interactions were observed, biweekly rates of $FeSO_4$ applied at 97.65 kg $FeSO_4$ ha^{-1}, in combination with 4.88 kg N ha^{-1}, were shown to result in Microdochium patch severity levels that are acceptable for golf course putting greens, while providing N for turfgrass recuperation; however, turf quality ratings were not deemed acceptable due to a loss of turf density or an unacceptable turf color. The mechanism by which $FeSO_4$ suppresses disease is not clear. Future studies will be necessary to determine if $FeSO_4$ suppresses Microdochium patch due to Fe, sulfate, a pH effect, or some other factor. Other studies researching carrier volumes and application timing may result in more precise information regarding the potential of $FeSO_4$ to inhibit Microdochium patch without a detriment to turf or soil quality.

Conflict of Interest

The authors declare that there is no conflict of interest.

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