Influence of Management Practices on Distribution of Fungicides in Golf Course Turf

Ling Ou and Richard Latin*

ABSTRACT
Fungicides are often applied to control root diseases that affect golf course turf. Post-application irrigation and wetting agents are suggested to improve fungicide performance by facilitating downward movement into the root zone. How irrigation and wetting agent treatments influence fungicide distribution in the turf profile remains unclear based on existing literature. The research objective was to investigate the influence of a wetting agent and post-application irrigation on the distribution of modern fungicides in a sand-based creeping bentgrass (Agrostis stolonifera L.) putting green. Fungicides used in two distinct experimental runs in field plots included azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin. Fungicide + irrigation, fungicide + wetting agent, and fungicide + irrigation + wetting agent treatment effects were compared with a fungicide-only treatment. Turf was sampled at –1, 0, 3, 7, 10, 14, 21, and 28 d after fungicide application. Core samples were collected and separated into three components—verdure/thatch, and soil at two depths, 2 to 5 and 5 to 8 cm. Fungicide was extracted from each turf component and analyzed thereafter using liquid chromatography–triple quadrupole mass spectrometry. Results showed that the majority of fungicide was captured by verdure/thatch, and that fungicide concentration in verdure/thatch was 1 to 2 orders of magnitude higher compared with other turf components. Further, in almost every case, there was no measurable effect of irrigation, wetting agent, or the combination on fungicide distribution in the turf profile. Research results can help improve understanding of fungicide distribution in turf and provide scientific context for recommendations regarding root disease control in golf course turf.

Core Ideas
• Most fungicide residues remained within the verdure/thatch layer.
• Irrigation and wetting agent had little effect on fungicide distribution.
• Distribution patterns for four modern fungicides were similar.
point of death (Smiley et al., 2005). In other cases, tank mixes of a wetting agent and a fungicide did not significantly affect fairy ring control compared with the fungicide alone, and fairy ring symptoms developed earlier with the wetting agent + fungicide treatment compared with the fungicide treatment alone (Miller et al., 2012). Published research on wetting agent effects on fungicides for control of infectious diseases is limited. Research on dollar spot (caused by *Clareedia* spp.) on creeping bentgrass (*Agrostis stolonifera* L.) and gray leaf spot on perennial ryegrass (*Lolium perenne* L.) showed that the addition of a wetting agent to the fungicide application resulted in no difference in disease severity compared with the fungicide alone (McDonald et al., 2006). A single season trial targeting spring dead spot of bermudagrass (*Cynodon dactylon* (L.) Pers.) showed that tank mixing fungicides with a wetting agent did not improve disease control compared with the fungicides alone (Earlywine and Miller, 2015). In another single season trial, a wetting agent alone was shown to reduce anthracnose severity on an annual bluegrass (*Poa annua* L.) putting green (Matroz et al., 2016).

Conventional wisdom holds that increasing water volume or applying supplemental irrigation will help move fungicide down through turf profile to address root infection by fungal pathogens. Most research on irrigation effects on turf disease focuses on foliar diseases (dollar spot, brown patch [caused by *Rhizoctonia solani*) or, in the case of root disease, the impact of irrigation timing on symptom expression (Davis and Deremoed, 1991). A single season report describing irrigation effects on the performance of fungicides for spring dead spot control showed that irrigation (amounts ranging from 0.20 to 0.79 cm [0.08–0.31 in]) applied immediately after fungicide spray did not result in any difference in levels of disease control (Walker, 2013). In another trial, Wong and Corza (2005) doubled the water volume (815–1630 L ha–1 [2–4 gal per 1000 ft2]) for fungicide sprays targeting summer patch on annual bluegrass, but observed no differences in the levels of disease control associated with water volume.

Consensus among turf management practitioners, advisors, and turf scientists presupposes that fungicides must penetrate well into the root zone to be effective against root diseases. Supporting evidence is scant, possibly because fungicide solubility and adsorption properties, combined with the highly organic nature of thatch (a loose matrix of organic matter, including dead and living roots) precludes downward movement of fungicides in the turf profile. Schumann et al. (2000) observed that most fungicide remained on the leaves and in the thatch despite supplemental irrigation (1.3 cm) following a spray of demethylase inhibitor (DMI) compounds. In a comprehensive examination of fungicide (propiconazole and mefenoxam) distribution in the turf profile over time, Gardner and Branham (2001) observed that post-application irrigation resulted in most of the fungicide remaining in the verdu/thatch and 0- to 2-cm depth of soil, and had no impact on the distribution of either compound. Similar results were reported for chlorothalonil residues by Wu et al. (2002). After sampling different components of the turf profile, including roots and soil, Latin and Ou (2018) observed that very little fungicide filtered below the verdu/thatch layer, even with post-application irrigation. Although there is ample knowledge regarding placement and persistence of fungicides in

<table>
<thead>
<tr>
<th>Turf component</th>
<th>OC†</th>
<th>pH</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verdu/thatch</td>
<td>7.85</td>
<td>7.53</td>
<td>94.4</td>
<td>1.8</td>
<td>3.8</td>
</tr>
<tr>
<td>2–5 cm</td>
<td>3.55</td>
<td>7.53</td>
<td>94.4</td>
<td>1.8</td>
<td>3.8</td>
</tr>
<tr>
<td>5–8 cm</td>
<td>3.59</td>
<td>7.55</td>
<td>94.4</td>
<td>2.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>

† Organic carbon. ‡ Since the verdure/thatch layer was not technically a soil component, the routine pH and soil texture analysis were not performed for this layer.
Irrigation (0.51 cm) was manually (watering can) applied to plots after fungicide application. Petri dishes were collected and sealed. Immediately (9-cm diam.) were placed in eight randomly selected plots to applied once for each run of the experiment. Glass Petri dishes were transported with dry tubes. Designated soil probes and cutting utensils were assigned and placed into respective pre-labeled 50-mL polypropylene tubes. Each sample core was immediately cut into a >8-cm depth. Each sample mixture was vortexed for 1 min before centrifuging at 855.27 × g (3000 rpm) for 5 min, then 1.5 mL of supernatant was added to 2 mL dispersive-SPE tubes, which contained 25 mg primary and secondary amine, 7.5 mg bulk carbograph, and 150 mg magnesium sulfate (high pigment, EN, Agilent Technologies). The new mixture was vortexed for 1 min and centrifuged at 3421.08 × g (6000 rpm) for 5 min. The new supernatant was transferred to 1.5 mL micro centrifuge tubes, and samples were stored at –20°C before analysis. Petri dish samples were extracted in 30 mL acetonitrile, diluted 30 times using acetonitrile and water mixture (80:20, v/v), and extracted the same manner as samples. Different concentrations of the standard solution were also extracted in the same manner as turf samples.

### Quantitative Analysis

The 6460 triple quad (QQQ) mass spectrometer (Agilent Technologies) was coupled with the Agilent 1200 series high performance liquid chromatography for fungicide analysis. Data analysis was performed by MassHunt Workstation Software Quantitative Analysis Version B.06.00/Build 6.0.388.0. The column used was Zorbax SB-Phenyl (4.6 × 150 mm, 5 µm, Agilent Technologies). The mobile phase included: buffer A, 90:10 (v/v), water: 50 mM ammonium acetate with 0.1% (v/v) formic acid; buffer B, 90:10 (v/v), acetonitrile: 50 mM ammonium acetate with 0.1% (v/v) formic acid. The flow rate was set at 0.8 mL min⁻¹, and injection volume was 10 µL. Specific fungicide parameters for multiple reaction monitoring transitions are shown in Table 3, including retention time, precursor ion, product ion, collision energy, and polarity. The four fungicide standards were obtained from AccuStandard, including azoxystrobin (100%), fluxapyroxad (98%), propiconazole (97.2%), and pyraclostrobin (99.5%). Metconazole was included as internal standard (98%), which was obtained from Sigma-Aldrich.

### Data Analysis

Statistical analyses were performed by SAS 9.4 (Cary, NC) with PROC analysis of variance (ANOVA) and General Linear Model (GLM) analyses. The response variable was the

<table>
<thead>
<tr>
<th>Fungicide</th>
<th>Product</th>
<th>Application rate</th>
<th>Water solubility</th>
<th>Koc‡</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azoxystrobin</td>
<td>Heritage WG</td>
<td>0.61 kg a.i. ha⁻¹</td>
<td>6.7 mg L⁻¹</td>
<td>423</td>
<td>78</td>
</tr>
<tr>
<td>Fluxapyroxad</td>
<td>Xzemplar</td>
<td>0.24 kg a.i. ha⁻¹</td>
<td>3.4 mg L⁻¹</td>
<td>728</td>
<td>183</td>
</tr>
<tr>
<td>Propiconazole</td>
<td>Banner Maxx</td>
<td>0.99 kg a.i. ha⁻¹</td>
<td>150.0 mg L⁻¹</td>
<td>955</td>
<td>72</td>
</tr>
<tr>
<td>Pyraclostrobin</td>
<td>Insignia SC</td>
<td>0.71 kg a.i. ha⁻¹</td>
<td>1.9 mg L⁻¹</td>
<td>9315</td>
<td>32</td>
</tr>
</tbody>
</table>

† The chemical properties were from AERU, 2018.
‡ Soil organic carbon sorption coefficient.

Field plots were sampled eight times during each experimental run, on –1, 0, 3, 7, 10, 14, 21, and 28 d after fungicide application (DAF). The –1 DAF sample was collected before fungicides were applied, and was used as a baseline for fungicide concentration in turf. The 0 DAF samples were taken after fungicide deposits dried on leaves, about 4 h after application. A soil probe (1.9 cm diam.) was used to sample the turf and soil profile to a >8-cm depth. Each sample core was immediately cut into three sections, verdure/thatch (2 cm), 2 cm to 5 cm, and 5 to 8 cm, and placed into respective pre-labeled 50-mL polypropylene tubes. Designated soil probes and cutting utensils were assigned to each of four treatments. Samples were transported with dry ice to the laboratory, weighed, and stored at –20°C before further processing.
Table 3. Fungicide parameters of multiple reaction monitoring transitions for mass spectrometer quantitative analysis.

<table>
<thead>
<tr>
<th>Fungicide</th>
<th>Retention time, min</th>
<th>Precursor ion</th>
<th>Product ion</th>
<th>Collision energy</th>
<th>Polarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azoxystrobin</td>
<td>9.9</td>
<td>404.1</td>
<td>372.2, 344.1, 329.1</td>
<td>15, 25, 30</td>
<td>Positive</td>
</tr>
<tr>
<td>Fluxapyroxad</td>
<td>9.7</td>
<td>379.9</td>
<td>248.1, 131</td>
<td>15, 20</td>
<td>Negative</td>
</tr>
<tr>
<td>Metconazole†</td>
<td>10.0</td>
<td>320.2</td>
<td>124.8, 70.1</td>
<td>30, 25</td>
<td>Positive</td>
</tr>
<tr>
<td>Propiconazole</td>
<td>10.3</td>
<td>342.1</td>
<td>159, 69.2</td>
<td>25, 20</td>
<td>Positive</td>
</tr>
<tr>
<td>Pyraclostrobin</td>
<td>10.8</td>
<td>388.1</td>
<td>194, 163</td>
<td>10, 25</td>
<td>Positive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Metconazole was included as internal standards for the other four fungicides.

Table 4. The F value, P-value, and coefficient of determination ($R^2$) for each fungicide from analysis of variance on log-transformed fungicide residue data.

<table>
<thead>
<tr>
<th>Source†</th>
<th>DF</th>
<th>Azoxystrorbin</th>
<th>Fluxapyroxad</th>
<th>Propiconazole</th>
<th>Pyraclostrobin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>1</td>
<td>106.21 &lt; 0.0001</td>
<td>26.74 &lt; 0.0001</td>
<td>97.85 &lt; 0.0001</td>
<td>3.85 0.0500</td>
</tr>
<tr>
<td>Trt</td>
<td>3</td>
<td>0.68 0.5636</td>
<td>13.89 &lt; 0.0001</td>
<td>1.99 0.1146</td>
<td>30.41 &lt; 0.0001</td>
</tr>
<tr>
<td>Comp</td>
<td>2</td>
<td>21160.04 &lt; 0.0001</td>
<td>1526.56 &lt; 0.0001</td>
<td>3983.91 &lt; 0.0001</td>
<td>2729.9 &lt; 0.0001</td>
</tr>
<tr>
<td>DAF</td>
<td>7</td>
<td>28.75 &lt; 0.0001</td>
<td>34.40 &lt; 0.0001</td>
<td>56.94 &lt; 0.0001</td>
<td>205.79 &lt; 0.0001</td>
</tr>
<tr>
<td>Trt × Run</td>
<td>3</td>
<td>2.20 0.0866</td>
<td>7.99 &lt; 0.0001</td>
<td>1.72 0.1616</td>
<td>5.33 0.0012</td>
</tr>
<tr>
<td>Trt × Comp</td>
<td>6</td>
<td>1.97 0.0674</td>
<td>4.65 0.0001</td>
<td>0.96 0.4492</td>
<td>5.96 &lt; 0.0001</td>
</tr>
<tr>
<td>Trt × DAF</td>
<td>21</td>
<td>0.45 0.9836</td>
<td>1.49 0.0737</td>
<td>1.17 0.2685</td>
<td>1.30 0.1646</td>
</tr>
<tr>
<td>Model $R^2$</td>
<td></td>
<td>0.79 0.83 0.92 0.91</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† Run, experimental run; Trt, treatment; Comp, turf component including verdure/thatch, 2–5 cm, and 5–8 cm; DAF, days after fungicide application.

concentration of four fungicides normalized to the dry weight of each component sample. Explanatory variables included experimental run, treatment (F, F + I, F + W, and F + I + W), turf component (verdure/thatch, 2–5 cm, and 5–8 cm) and DAF (–1, 0, 3, 7, 10, 14, 21, and 28). There were four replicates in the analysis. The ANOVA was run separately for each fungicide. In addition to ANOVA for the overall experiment, differences among treatments were examined through GLM analysis at each individual sample day. Log transformation was performed for fungicide residue data to increase normality. However, untransformed data were presented for figures.

**RESULTS AND DISCUSSION**

**Fungicide Recovery**

Standard curves of fungicide concentration and relative response from the mass spectrometer were quadratic or linear over the range of 3.3 to 3333.9 ng mL$^{-1}$ with correlation coefficients $R^2 > 0.999$ for all fungicides. The limits of fungicide quantification were 3.3, 3.0, 3.3, and 3.3 ng mL$^{-1}$ for azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin, respectively. Relative to the spray quantities, Petri dish samples recovered 81, 120, 77, and 88% for azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin, respectively. Considering field experimental errors of spraying, sampling, laboratory errors of extraction, and instrumental analysis, this recovery rate is acceptable, and it demonstrates accuracy and appropriateness of the experimental methods.

**Analysis of Variance**

An overall ANOVA table is shown (Table 4) with F-values, P-values, and coefficients of determination for each fungicide on log-transformed residue data. The variables include experimental run, treatment (F, F + I, F + W, and F + I + W), turf component (verdure/thatch, 2–5 cm, 5–8 cm), and DAF. In the ANOVA table, the component variable had the highest F value with $P < 0.0001$ for all fungicides, indicating significantly different residue amounts associated with the three turf components in all cases. The DAF was also significant for all fungicides, and described a general decline in fungicide residues over time. Residue levels associated with run and treatment were significant for some, but not all, fungicides. Model $R^2$ values (0.79, 0.83, 0.92, and 0.91 for azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin, respectively) indicated that the majority of variations in the data set were explained by model variables.

**Temporal and Spatial Distribution of Fungicides**

Fungicide residue distribution in three components (verdure/thatch, 2–5 cm, and 5–8 cm) for four fungicides and two runs over the course of the experiment are presented in Fig. 1 (and Supplemental Fig. S2–S8). The –1 DAF residue data established a baseline for fungicide concentration. Regardless of the four treatments, all fungicides showed similar patterns of spatial and temporal distribution: Most of the fungicide was captured in the verdure/thatch layer, with residue amounts that were 1 to 2 orders of magnitude higher compared with amounts in the 2–5- and 5–8-cm components. On average, fungicide concentrations in the verdure/thatch measured 21, 7, 15, and 64 times greater compared with the 2–5-cm component for azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin, respectively. Also, concentrations in verdure/thatch were 19, 28, 22, and 109 times greater than concentrations observed in the 5–8-cm component for azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin, respectively.

Fungicides tended to remain within the verdure/thatch layer, most likely due to their low water solubility and high sorption coefficients. The water solubility is 6.7, 3.4, 150.0, and 1.9 mg L$^{-1}$ for azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin, respectively (AERU, 2018), ranging from very low to low. The $K_{oc}$ values are 423, 728, 955, and 9315 for azoxystrobin, fluxapyroxad, propiconazole, and pyraclostrobin, respectively (AERU, 2018), and are classified as moderate to high. The large amount of OC in the verdure/thatch layer contributed to sorption of the majority of fungicide residues in this component. The analysis showed that OC was 7.85, 3.55, and 3.59% for verdure/
thatch, 2 to 5 cm, and 5 to 8 cm, respectively (Table 1). Normally a mineral soil has OC ranging from 0.29 to 2.9%, and sandy soil often has OC < 0.58% (Sparks, 2003); therefore, 7.85% OC in the verdure/thatch was very high (due to the high amount of living and dead plant tissues present). In a related study, azoxystrobin, propiconazole, prochloraz, and trifloxystrobin sorbed 10 to 30 times more in sand-based root zones amended with garden compost compared with straight sand (Aamlid et al., 2009).

One important observation from the figures was that fungicide residue remained relatively high in verdure/thatch at the end of the sampling period, although it declined over time. Published research in the disciplines of environmental fate and bioremediation of pesticides emphasizes that amounts detected or measured with modern instrumentation following meticulous laboratory extraction with concentrated organic solvents (80% acetonitrile) are not related to activity or efficacy against a target pest species (Harmsen, 2007; Harmsen et al., 2005). Furthermore, research has established that bioavailability decreases over time as a compound ages (Alexander, 2000). Despite the presence of active ingredients in the verdure/thatch over 28 d in this study, practical empirical research on disease control with fungicides cautions against expectation of fungicide activity weeks beyond the application date.

Treatment Effects on Fungicide Distribution

Differences among treatments for each fungicide over 8 sample days in three turf components for Runs 1 and 2 are shown in Fig. 2–7 and summarized in Table 5. Results presented in Table 5 are based on statistical analysis performed on log-transformed data, whereas untransformed data were used to construct the figures (Fig. 2–7). On most sample days, there was no difference in the amount of observed residues among treatments, i.e., application of wetting agent and/or post-spray irrigation had little or no significant effects on fungicide distribution in the turf profile. Only a few exceptions appeared on certain sample days; however, those differences were not consistent throughout the sampling period, or among fungicides. Furthermore, Fig. 2–5 suggest that where differences among treatments did occur, the variations were minimal.

For the verdure/thatch component, residues observed in the F treatment were comparable to residues in F + I, F + W, and F + I + W treatments—for all fungicides and for all sampling dates and over both Run 1 (Fig. 2) and Run 2 (Fig. 3). Similar results were observed within the 2- to 5-cm soil component (Fig. 4 and 5), and likewise for the 5- to 8-cm component (Fig. 6 and 7). The mass of evidence shows that post-application irrigation and wetting agent treatments did not affect fungicide distribution consistently in the profile throughout the sampling period. Whether results are represented after analysis of transformed data (Table 5) or treatment means (Fig. 2–7), the interpretation remains the same—wetting agent and post application irrigation treatments applied in this research had little or no effect on fungicide distribution.

Our work supports results by Gardner and Branham (2001), who concluded that two fungicides (propiconazole and mefenoxam) were not influenced by irrigation regime, i.e., most of the fungicide remained in the thatch layer or upper 2 cm of soil. In a 120-d environmental fate study by Wu et al. (2002),

![Graphs showing fungicide residue distribution](image-url)
Fig. 2. Fungicide distribution over the Run 1 sampling period in the verdure/thatch component for each of four treatments (F = fungicide-only, F + I = fungicide + irrigation, F + W = fungicide + wetting agent, F + I + W = fungicide + irrigation + wetting agent) for four compounds: (a) azoxystrobin; (b) fluxapyroxad; (c) propiconazole; and (d) pyraclostrobin. Error bars denote the standard deviation for four replications.

Fig. 3. Fungicide distribution over the Run 2 sampling period in the verdure/thatch component for each of four treatments (F = fungicide-only, F + I = fungicide + irrigation, F + W = fungicide + wetting agent, F + I + W = fungicide + irrigation + wetting agent) for four compounds: (a) azoxystrobin; (b) fluxapyroxad; (c) propiconazole; and (d) pyraclostrobin. Error bars denote the standard deviation for four replications.
Fig. 4. Fungicide distribution over the Run 1 sampling period in the 2–5 cm component for each of four treatments (F = fungicide-only, F + I = fungicide + irrigation, F + W = fungicide + wetting agent, F + I + W = fungicide + irrigation + wetting agent) for four compounds: (a) azoxystrobin; (b) fluxapyroxad; (c) propiconazole; and (d) pyraclostrobin. Error bars denote the standard deviation for four replications.

Fig. 5. Fungicide distribution over the Run 2 sampling period in the 2–5 cm component for each of four treatments (F = fungicide-only, F + I = fungicide + irrigation, F + W = fungicide + wetting agent, F + I + W = fungicide + irrigation + wetting agent) for four compounds: (a) azoxystrobin; (b) fluxapyroxad; (c) propiconazole; and (d) pyraclostrobin. Error bars denote the standard deviation for four replications.
Fig. 6. Fungicide distribution over the Run 1 sampling period in the 5–8 cm component for each of four treatments (F = fungicide-only, F + I = fungicide + irrigation, F + W = fungicide + wetting agent, F + I + W = fungicide + irrigation + wetting agent) for four compounds: (a) azoxystrobin; (b) fluxapyroxad; (c) propiconazole; and (d) pyraclostrobin. Error bars denote the standard deviation for four replications.

Fig. 7. Fungicide distribution over the Run 2 sampling period in the 5–8 cm component for each of four treatments (F = fungicide-only, F + I = fungicide + irrigation, F + W = fungicide + wetting agent, F + I + W = fungicide + irrigation + wetting agent) for four compounds: (a) azoxystrobin; (b) fluxapyroxad; (c) propiconazole; and (d) pyraclostrobin. Error bars denote the standard deviation for four replications.
residues of chlorothalonil were not detected below the 0- to 2-cm thatch layer after daily irrigation (amount not specified); however, metalaxyl was detectable at the 2- to 20-cm soil depth. Chlorothalonil has properties similar to the fungicides studied in this research (solubility of 0.81 mg L⁻¹, 

\[ K_{oc} \] of 2632), but metalaxyl is highly soluble (8400 mg L⁻¹) and has low adsorption properties \((K_{oc} = 162)\). In an investigation of residues in Kentucky bluegrass \((Poa pratensis L.)\) with a well-defined 3-cm thatch layer, Schumann et al. (2000) observed almost no fungicide in roots and soil below the thatch despite application of 1.3 cm irrigation immediately after fungicides were applied. Results of a more recent study showed that irrigation had minimal and inconsistent effects on fungicide residues in roots and soil below a thin (2 cm) verdures/thatch layer of a sand-based creeping bentgrass putting green (Latin and Ou, 2018). The two field investigations that specifically address fungicide efficacy against root diseases as affected by supplemental irrigation (Walker, 2013) or increased water volume (Wong and Corza, 2005) clearly show that irrigation and increased water volume were not necessary to achieve excellent disease control. The body of evidence in published research, supported by results reported here, challenges the conventional wisdom that post application irrigation will help transport fungicides downward in the profile to reach roots below the thatch layer.

The benefit of wetting agent application in terms of improved turf quality, amelioration of localized dry spots, and to some extent fairy ring development has been described in agronomic literature (Kostka et al., 1997; Karnok and Tucker, 1999). Reports on fungicide and wetting agent effects on fairy ring development are ample, but results are not consistent. Published research on the effects of wetting agent and fungicide on control of infectious root diseases is limited. Where wetting agent was tank mixed with fungicides in an attempt to control spring dead spot of bermudagrass, adding the wetting agent did not result in improved disease control or turf quality when compared to fungicides alone (Earlywine and Miller, 2015). Similar conclusions could be drawn from a trial targeting southern blight (admittedly a disease of crowns and stems) on annual bluegrass (Wong and Rios, 2008). The work reported here, and that described by Latin and Ou (2018), do not support the notion that wetting agents contribute to root disease control by facilitating fungicide distribution in the turf profile. Given high OC content of verdures/thatch, and the solubility and adsorption properties of fungicides prescribed for controlling root diseases (not caused by oomycetes), significant wetting agent effects are unlikely. However, this research was conducted with a single wetting agent applied as directed by the product label, 1 d prior to fungicide sprays, and not tank mixed with fungicides. Only comprehensive research on tank mixing fungicides with a variety of wetting agents against root diseases will be conclusive.

Irrigation effects warrant further consideration. The body of evidence confirms that the thatch layer represents a formidable barrier to further penetration of fungicides into the root zone. Fungicides are not likely to leach—even in a sand-based system.
If the primary target is root disease, then supplemental irrigation may help wash spray deposits from leaves, where they will accumulate in thatch, and where they may suppress growth of root pathogens and, if xylem mobile, could be absorbed by roots to address existing infections and protect leaves and stems. Since fungicides accumulate in thatch, excess irrigation is not likely to dilute concentrations to ineffective levels. Most fungicide sprays target both foliar and root pathogens. Therefore, supplemental irrigation after fungicide application may diminish chemical protection of leaves and stems.

**CONCLUSION**

This research was designed to investigate effects of a wetting agent treatment and post-application irrigation on distribution of four modern fungicides in a sand-based creeping bentgrass putting green. For all compounds, most of the fungicide was retained within the verdure/thatch layer. The research also demonstrated that applying a wetting agent 1 d prior to fungicide application, and irrigating immediately after the fungicide spray, had limited effects on fungicide distribution in the turf profile. In almost all cases, there was no measurable impact of treatment, with a few exceptions at some individual sampling dates. The high adsorption properties and low water solubility of most fungicides preclude movement through the highly organic thatch layer, regardless of irrigation or wetting agent treatment. Supplemental irrigation and wetting agent applications are important to maintaining healthy turf; but the notion that they improve fungicide performance by affecting distribution in the turf profile is not supported by this research.

**SUPPLEMENTAL MATERIAL**

Fig. S1. Daily temperature and precipitation for (a) Run 1 and (b) Run 2.

Fig. S2. Azoxystrobin residue distribution over the entire sampling period of Run 1 in three turf profile components (verdure/thatch, 2–5 cm, and 5–8 cm), for each of four treatments: (a) fungicide-only; (b) fungicide + irrigation; (c) fungicide + wetting agent; (d) fungicide + irrigation + wetting agent. Error bars denote the standard deviation for four replications.

Fig. S3. Azoxystrobin residue distribution over the entire sampling period of Run 2 in three turf profile components (verdure/thatch, 2–5 cm, and 5–8 cm), for each of four treatments: (a) fungicide-only; (b) fungicide + irrigation; (c) fungicide + wetting agent; (d) fungicide + irrigation + wetting agent. Error bars denote the standard deviation for four replications.

Fig. S4. Fluxapyroxad residue distribution over the entire sampling period of Run 1 in three turf profile components (verdure/thatch, 2–5 cm, and 5–8 cm), for each of four treatments: (a) fungicide-only; (b) fungicide + irrigation; (c) fungicide + wetting agent; (d) fungicide + irrigation + wetting agent. Error bars denote the standard deviation for four replications.

Fig. S5. Fluxapyroxad residue distribution over the entire sampling period of Run 2 in three turf profile components (verdure/thatch, 2–5 cm, and 5–8 cm), for each of four treatments: (a) fungicide-only; (b) fungicide + irrigation; (c) fungicide + wetting agent; (d) fungicide + irrigation + wetting agent. Error bars denote the standard deviation for four replications.

Fig. S6. Pyraclostrobin residue distribution over the entire sampling period of Run 1 in three turf profile components (verdure/thatch, 2–5 cm, and 5–8 cm), for each of four treatments: (a) fungicide-only; (b) fungicide + irrigation; (c) fungicide + wetting agent; (d) fungicide + irrigation + wetting agent. Error bars denote the standard deviation for four replications.

Fig. S7. Pyraclostrobin residue distribution over the entire sampling period of Run 2 in three turf profile components (verdure/thatch, 2–5 cm, and 5–8 cm), for each of four treatments: (a) fungicide-only; (b) fungicide + irrigation; (c) fungicide + wetting agent; (d) fungicide + irrigation + wetting agent. Error bars denote the standard deviation for four replications.

Fig. S8. Pyraclostrobin residue distribution over the entire sampling period of Run 2 in three turf profile components (verdure/thatch, 2–5 cm, and 5–8 cm), for each of four treatments: (a) fungicide-only; (b) fungicide + irrigation; (c) fungicide + wetting agent; (d) fungicide + irrigation + wetting agent. Error bars denote the standard deviation for four replications.

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