EFFECT OF SURFACTANT ON FINGERED FLOW IN LABORATORY GOLF GREENS

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Preferential flow in golf greens causes turfgrass quality deterioration and shortens solute travel time. Little is known how surfactants affect the flow pattern in golf greens. This study visualizes the changes in flow patterns and compares leaching of a nonadsorbed and an adsorbed chemical as a result of the addition of a nonionic surfactant in a simulated United States Golf Association (USGA) putting green profile in a two-dimensional sand slab chamber. The USGA putting greens have three distinct layers that become coarser with depth. The addition of the surfactant changed the unstable preferential flow pattern to a uniform flat wetting front in the first 11 cm. Below this, small perturbations occurred, and at a depth of 17 cm, the wetting front became unstable and formed six fingers. After the first 17 cm, the infiltration process was not affected by the addition of the surfactant. Water infiltrated into the second layer as a wavy front and developed a single finger at the third layer. After the irrigation was stopped and water reapplied, the water followed the same pathways established during the first infiltration cycle. Chloride moved two times more slowly in the surfactant-treated profile compared with the nontreated profile. A second application of the surfactant at the same rate did not alter the flow patterns. The study showed that surfactants can provide an inexpensive way to decrease the travel velocity of the pollutants and increase the efficacy of water and applied chemicals through coarse-textured turfgrass profiles. (Soil Science 2002;167:572-579)

Key words: Preferential flow, unstable wetting front, vadose zone, surfactant, turfgrass.

SURFACTANTS have been used extensively in turfgrass management to improve both problematic localized dry spots (LSD) (Wilkinson and Miller, 1978), and water infiltration (Zartman and Bartsch, 1990) by reducing the hydrophobicity of the thatch layer (Pelshek et al., 1962; Miyamoto, 1985). Many modern United States Golf Association (USGA) golf putting greens are constructed with a peat-amended sandy root zone layer (0–30 cm), followed by 5 cm of coarse sand and 10 cm of gravel (USGA Greens Section Staff, 1993). These USGA greens exhibit a hydrophobic response upon drying (Wilkinson and Miller, 1978; York and Canaway, 2000; Cisar et al., 2000) and require the addition of surfactants to improve their wettability.

Because of increased awareness and concern for the environmental fate of pesticides and turf-applied chemicals (Flipse et al., 1984; Abrams, 1991; Petrovic and Larson-Kovach, 1996), the effects of surfactants on water and contaminant transport need to be investigated. Present information about the effects of surfactants on the mobility of synthetic chemicals is limited. Sharma et al. (1985) found that an anionic (sodium dodecyl sulfate) and a nonionic (manoxol 'OT') surfactant reduced the movement of several phosphorus pesticides in a sandy loam and a silt loam soil, by inhibiting the capillary action of water. Furthermore, Takeuchi et al. (1989) found that a nonionic surfactant promoted the efficacy and move-
ment of several growth retardants into a volcanic ash soil. Cisar et al. (2000) observed that commercially available surfactants increased turfgrass quality and reduced the percentage of dry spot incidence through a period of drought that induced soil-water repellency symptoms and, subsequently, through a period of recovery.

Water and solutes can move preferentially in fingered flow through coarse-textured soil (Hill and Parlane, 1972; Selker et al., 1992; Blackwell, 2000) and water repellent profiles (Hendricks et al., 1993; Bauters et al., 1998; Wang et al., 2000; Feng et al., 2002). In fingered flow, only a fraction of the soil participates in the infiltration/percolation process, thereby increasing the downward velocity of the contaminant.

Fingered flow was the primary mechanism of water and solute transportation for the USCA putting greens profiles (Nektarios et al., 1999). Finger formation is caused by instability of the wetting front enhanced by gravity and stabilized by surface tension (Selker et al., 1992). Surfactants reduce the surface tension of the liquid and decrease the contact angle (DeBano, 2000) and, therefore, influence water and solute movement through sand profiles. Although surfactants are applied in great quantities on golf greens (Kostka, 2000) their behavior in the soil profile has not been well researched because of the lack of visualizing techniques.

The objective of this study was twofold: (i) to visualize and analyze the effects of a nonionic surfactant on water infiltration and contaminant transport through the trilayered profile of a golf putting green, and (ii) to compare the infiltration flow pattern with and without the use of a surfactant.

MATERIALS AND METHODS

The experimental procedures were similar to Nektarios et al., (1999) except for the use of the surfactant. Specifically, a sand profile similar in grain size composition to a golf putting green was simulated in a two-dimensional glass chamber 50 cm wide, 46 cm high, and 1.2 cm thick. The bottom of the chamber was separated into five different sections, and leachate was collected through a series of five funnels into a fraction collector (ISCO 1850, Instrumentation Specialties Co., Lincoln, NE).

The soil profile consisted of three layers of silica sand, with medium sand (0.3–0.43 mm) at 0 to 30 cm, followed by 5 cm of coarse sand (0.85–1.4 mm), and 10 cm of very coarse sand (1.4–2.0 mm) at the bottom. Silica sand was washed with hot water and soap for 30 min, then with hot water and bubbling air for 40 min, followed by cold water for 30 min, and finally rinsed twice with distilled water. The washed sand was then oven dried at 100 °C. Washing the sand was necessary in order to exclude any impurities and improve light transmission. At the end of the processes, the sand did not exhibit any signs of hydrophobicity.

To ensure uniform packing, the oven-dried sand was poured into the chamber through a hopper and an extension having three randomizing screens. The sand was gravity packed by adding an additional 15-cm layer, and the excess sand was removed with glass tubing attached to a vacuum pump.

The chamber was placed in front of a bank of high output fluorescent lights (40,000 Hz), and water movement through the profile was detected by light intensity differences, which has been found to be proportional to water content (Glass et al., 1989). A calibration curve that correlated the normalized light intensity to moisture content was obtained for the sand that was used in the top layer from complimentary one-dimensional experiments (Nektarios et al., 1999). Light intensity data were recorded with a black and white video camera and a lap recorder on videotapes and then processed with IRIS Video Image Software (Data Translation Inc., Marlboro, MA) for wetting front and finger velocity, and for structure determination.

A nonionic surfactant, water, and tracers were applied uniformly on the top of the chamber using a pesticide nozzle (Teejet XR8001, Spraying System Co., Wheaton, IL) attached to a chain-driven shuttle. The flow rate was manipulated with a delay switch. At the beginning of the experiment, 3 mL of a solution containing a commercially available nonionic surfactant (Aquagro® L, Aquatrols Corp. of America, Pennsauken, NJ) was applied at the recommended rate of 8 mL of product L⁻¹ through the irrigation system. The application of the nonionic surfactant was equivalent to 4 mL of product m⁻². Immediately after the application of the nonionic surfactant, the irrigation system was cleaned with distilled water, and irrigation was resumed at a rate of 2.5 cm h⁻¹.

When the infiltrating water reached the bottom of the slab, Cl⁻ (0.1 M) as CaCl₂ and FD&C Blue Dye #1, at a concentration of 500 mg L⁻¹ were applied simultaneously. Chloride was used as a nonadsorbing tracer with transport properties similar to nitrates, whereas blue dye served a dual role of visualizing the flow path in the wetted
profile and as a surrogate for a weakly adsorbed pesticide (Andreini and Steenhuis, 1990; Flury, 1996). Both Cl⁻ and blue dye were applied for 160 min at a rate of 2.5 cm h⁻¹. Irrigation with distilled water was resumed immediately after the termination of the tracer application without interrupting the irrigation. Irrigation was stopped when all dye residues were removed.

Chloride was analyzed with a coulometric titration using a chloridometer (Buchler, Model 442-5000, Buchler Instruments, Lenexa, KS) following the recommendations of the manufacturer. Blue dye was analyzed colorimetrically using a spectrophotometer (Milton Roy, Spectronic 601) at a wavelength of 430 or 630 nm, depending on the blue dye concentration.

After 10 days, the nonionic surfactant was applied for a second time using procedures described before except that the blue dye and Cl⁻ were applied with the first irrigation water to aid in visualizing the effect of the nonionic surfactant on the previously established flow field.

RESULTS AND DISCUSSION

The golf putting greens we constructed did not show any signs of hydrophobicity, and we continued to observe preferential flow when no surfactants were added (Nektarios et al., 1999). Most golf greens will be hydrophobic and even more prone to fingered flow (Bauters et al., 1998; Wang et al., 2000). Several studies have shown that the unstable flow pattern in hydrophilic coarse grained soils is the same as in hydrophobic soils (DeBano, 2000, Bauters et al., 2000) Thus, our findings are also applicable for golf greens that are hydrophobic. The effect, if any, will be more pronounced under hydrophobic conditions.

Movement of Water Amended with Nonionic Surfactant into the Dry Profile

Water amended with the nonionic surfactant infiltrated as a uniform wetting front for the first 11 cm in the oven-dried sand (Fig. 1A). Two perturbations appeared at the two edges of the wetting front, which had approximately the same water content as the rest of the front. These projections were, therefore, likely not instabilities (fingers) but rather the result of minimal discrepancies on the uniformity of the water distribution system near the edges of the chamber (Fig. 1B). The wide wetting front is in stark contrast with the finger flow that was observed by Nektarios et al. (1999) (Figs. 1A' and 1B') using the same sand profile and similar flow rate (2.8 cm h⁻¹). Light intensity measurements across the wetting front at 7-cm depth showed that the water content was uniform when the surfactant was used (Fig. 2). The two small spikes at the two edges of the front in Fig. 2 correspond to the two projections at each edge of the front and are a result of the slightly higher flux in these regions.

The velocity of the stable wetting front at the first 11 cm was fairly constant (0.23 cm min⁻¹) and was four times slower than the water velocity (0.8 cm min⁻¹) in the same profile without the use of the nonionic surfactant (Nektarios et al., 1999). The moisture content for the wide uniform front was approximately 0.18 cm³ cm⁻³, whereas the fingered front was close to saturation at 0.36 cm³ cm⁻³.

At 11 cm below the surface, small instabilities formed at the wetting front, which developed into fingers at the 17-cm depth (Figs. 1B and 1C). This indicated that the effect of the nonionic surfactant became less effective either due to sufficient dilution or due to H-bonding of the nonionic surfactant with water films coating the sand particles (Valoras et al., 1969; Chu and Su, 2001). Two fingers were formed from the perturbations at the sides of the front and a third finger was formed in the middle of the wetting front (Fig. 1C). At a depth of 22 cm, three more fingers developed, giving a total of six fingers in the top layer of the medium sand. The fingers were much closer together than without the use of the nonionic surfactant reported by Nektarios et al., 1999 (Fig. 1C').

When the fingers reached the interface between the medium and coarse sand, they moved sideways over the interface (Fig. 1C). After a capillary fringe of 7.6-cm height was formed, water entered into the second layer from two points as fingers (Fig. 1D). A second capillary fringe developed above the second interface and a single finger was formed in the third layer (Fig. 1E). The flow paths through the second and third layers were similar to earlier studies where the nonionic surfactant was not used (Nektarios et al., 1999).

Finger width was measured 1.6 cm above the finger tip (Table 1) and increased initially with time and distance traveled and then became constant. The fingers that developed with the use of the surfactant had half the width of the primary one observed with nonamended water infiltration (Nektarios et al., 1999). This is consistent with the theory of Parlane and Hill (1976) where a low flux through the finger results in a small finger, assuming that the contact angle and the surface tensions are the same. This is another
Fig. 1. A nonionic surfactant amendment caused a uniform wetting front with constant water content for the first 11 cm.
A' Finger flow induction in nonamended water infiltration (Nektarios et al., 1999).
B' Wetting front exhibiting minor instabilities between 11 and 17 cm.
B' Finger flow development in nonamended infiltration (Nektarios et al., 1999).
C Dilution of the nonionic surfactant permits the formation of several fingers after 17 cm depth.
C' Expression of two secondary fingers when the primary finger reaches the first interface in nonamended infiltration (Nektarios et al., 1999). (continued)
indication that the added surfactant is not effective anymore. Otherwise, the finger size would have been larger (Bauters et al., 1998).

**Dye Movement in a Surfactant-Treated Wetted Profile**

After the infiltrating water reached the bottom of the chamber, blue dye and chloride were applied. The blue dye was used to visualize water movement in the wetted profile and to simulate the behavior of a weakly absorbed pesticide.

The dye followed the same pathways that were developed during the infiltration in the dry sand (Fig. 1F). A wide uniform wetting front was observed in the first 17 cm of the top layer, which was then funneled through the fingers that developed in the first infiltration cycle. The percolation process through the first layer was much faster in the wetted profile, primarily because the capillary fringe had already developed. Percolation time to the first interface was approximately the same for water in the dry sand and dye in the wetted profile. However, it took approximately 120 min for the development of the capillary fringe in the dry sand while the dye in the wetted profile infiltrated immediately into the second layer. In the second layer, dye from both ends converged towards the single finger that was already established into the third layer. The dye from the left side traveled laterally 45 cm over the horizontal interface (Fig. 1G) before it was funneled into the single finger that was formed in the bottom layer.

**Dye Movement in the Wetted Profile after the Second Application of the Nonionic Surfactant**

In order to examine if we could wet the profile uniformly below the 17 cm depth, the nonionic surfactant was added again. The second application had no effect on the pathways that were initially formed in the dry sand. The dye that was applied after the second application of the wetting agent infiltrated as a uniform wetting front.

Fig. 1.—Continued D Infiltration of the nonionic surfactant amended water into the second layer as an unstable wetting front.
E Infiltration as a single finger in the third layer of the amended water.
F Dye movement in the wetted profile with minimal retardation at the first interface.
G Sideways movement of the dye over the second interface and its funnelling through a single finger into the third layer.
for the first 17 cm and then followed the established finger pathways. The dye passed immediately into the second and third layers without converging toward any of the two ends of the profile, creating several fingers at the bottom layer. The change in the flow pattern in the third layer (several fingers rather than a single one) was attributed to the increased water input that was used to clean the dye residues from the first study rather than to the nonionic surfactant effects.

Concentrations of Chloride and Dye in the Leachate

After the first application of the nonionic surfactant, leachate was collected from one of the five sections of the slab chamber near the finger. The remaining four sections did not provide any leachate even though the dye had adsorbed in the soil. Dye and chloride were detected in the leachate at the same time, approximately 200 min after their application, which was twice as long (Fig. 3) as in the study where nonionic surfactant was not used (Nektarios et al., 1999). Since the flux was approximately equal for both experiments, the difference in travel time was related to the flow differences observed at the top layer caused by the addition of the nonionic surfactant.

After the second application of the nonionic surfactant, two of the five sections at the bottom

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Comparison of flow characteristics between wetting agent amended and nonamended water infiltration</th>
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<tbody>
<tr>
<td></td>
<td>Average velocity (cm/min)</td>
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<tr>
<td>Nonamended flow</td>
<td>0.76</td>
</tr>
<tr>
<td>Finger 1</td>
<td>0.76</td>
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<tr>
<td>Finger 2</td>
<td>0.39</td>
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<tr>
<td>Finger 3</td>
<td>0.24</td>
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<tr>
<td>Wetting agent amended flow</td>
<td>0.23</td>
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<tr>
<td>Uniform wetting front</td>
<td>0.23</td>
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<tr>
<td>Finger 1</td>
<td>0.32</td>
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<tr>
<td>Finger 2</td>
<td>0.28</td>
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<tr>
<td>Finger 3</td>
<td>0.19</td>
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<tr>
<td>Finger 4</td>
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<td>Finger 5</td>
<td>0.21</td>
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<td>Finger 6</td>
<td>0.30</td>
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Fig. 3. Chloride and dye breakthrough curves (BTCs) after the first application of the nonionic surfactant. A chloride BTC for water infiltration without the addition of a nonionic surfactant is provided for comparison from Nektarios (1994).

Fig. 4. Chloride and dye breakthrough curves after the second application of the nonionic surfactant. Leaching occurred in only two of the five sections of the chamber (Sections 4 and 5).
of the chamber had outflow (Fig. 4). The dye and chloride broke through again at approximately the same time as in the first application of the nonionic surfactant. The slope of the breakthrough curves (BTCs) was steeper than with the first application, which could be explained by the changes in the wetting patterns at the third layer.

SUMMARY AND CONCLUSIONS

The way golf greens are constructed, with three layers increasing in coarseness with depth, is apt to result in fingered flow. We show that even when the soil is hydrophilic, there can be preferential fingered flow in the top layer. Literature has shown that when the soil becomes more hydrophobic, fingered flow becomes even more likely. In the two coarser bottom layers, preferential flow will likely always occur, starting with the first water application after construction. The upper layer restricts the flow so that the flow in the coarser second layer is always unsaturated, causing the typical unstable fingered flow configuration already observed in the 1970s by Hill and Parlange (1972).

Application of a surfactant in irrigation water to a profile with existing preferential flow paths will not cause the wetting of the soil to become more uniform because the water (and surfactant) will simply follow the previously established path and the surfactant will not enter the dry areas of the soil. Only when there are no existing preferential flow paths (dry soil in our case or uniformly wet soil when golf courses are irrigated very frequently and the profile never dries out), adding a surfactant in the water might prevent fingers from forming fingered flow.

REFERENCES


