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FUNGICIDE AND NUTRIENT TRANSPORT WITH RUNOFF FROM CREEPING BENTGRASS TURF

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ABSTRACT

The detection of pesticides and excess nutrients in surface waters of urban watersheds has lead to increased environmental concern and suspect of contaminant contributions from residential, urban, and recreational sources. Highly managed biotic systems such as golf courses and commercial landscapes often require multiple applications of pesticides and nutrients that may be transported with runoff to surrounding surface waters. The objective of this study was to evaluate the off-site transport and impact of flutolanil, (N-[3-(1-methylethoxy) phenyl]-2-(trifluoromethyl) benzamide), soluble phosphorus, ammonium nitrogen, and nitrate nitrogen with runoff from creeping bentgrass turf managed as a golf course fairway. Runoff from plots aerated with hollow tines and pre-wetted to field capacity 48 h prior to fertilizer and fungicide application contained the chemicals of interest in the initial runoff and throughout the runoff events. Edge-of-plot runoff contained phosphorus concentrations that were greater than USEPA water quality criteria to limit eutrophication, nitrate nitrogen levels below the drinking water standard to prevent blue baby syndrome and flutolanil concentrations below the median lethal concentration for 6 of 7 aquatic organisms assessed. Extrapolation of measured runoff loads to estimated environmental concentrations in a receiving surface water (runoff from 10-ha area into a 1-ha surface area x 2-m depth) resulted in phosphorus concentrations remaining above levels associated with increased algal growth and eutrophication. Quantitative data collected from this study provides information on the transport of chemicals with runoff from turf that can be used in model simulations to predict non-point source pollution potentials and assess ecological and health risks.

Abbreviations: ANOVA, analysis of variance; EEC, estimated environmental concentration; HT, hollow tine; LC50, median lethal concentration; NH_4-N, ammonium nitrogen:, NO_3-N, nitrate nitrogen; sol-P, soluble phosphorus; ST, solid tine; USEPA, United States Environmental Protection Agency

Keywords: bentgrass, flutolanil, fungicide, nitrogen, phosphorus, runoff

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INTRODUCTION

Eutrophication of surface waters, increased occurance of algal blooms, and detection of pesticides in water resources has lead to increased environmental concern and greater suspect of contaminant contributions from residential, urban, and recreational sources, in addition to the traditional agricultural and industrial inputs (Correl, 1998; Sharpley, 2000; Beman et al. 2005; Pensa and Chambers, 2004; Varlamoff et al., 2001; Hoffman et al., 2000, Gilliom et al. 2006). Nutrients (nitrogen and phosphorus) and plant protection products (pesticides: fungicides, herbicides, insecticides) are often applied to highly managed biotic systems such as golf courses, commercial landscapes, and agricultural crops. Golf course turf often requires multiple applications of pesticides at rates that exceed those typically found in agricultural or home environments (Gianessi et al., 1996; Barbash and Resek, 1996).

Fairways comprise approximately one-third of a typcial golf course (Watson et al., 1992), which may be adjacent to surface waters such as ponds, streams, and lakes. Runoff from golf course fairways may contribute to the degradation of water quality in surrounding surface waters depending on the quantity of runoff and level of contaminants. Reduced surface runoff has been observed in turf compared with tilled soils (Gross et al., 1990). Creeping bentgrass (*Agrostis palustris* Huds.) maintained as a golf course fairway has been shown to reduce surface runoff compared to perennial ryegrass (*Lolium perenne* L.) (Linde et al., 1995). However, golf courses have also been shown to contribute to increased nutrient loads in receiving surface waters. King et al. (2001) observed storm runoff from a golf course in Texas contributed an estimated 2.3 kg ha^{-1} of nitrate and nitrite nitrogen and 0.33 kg ha^{-1} of orthophosphate to a stream during a 13-month period. Excess nitrogen and phosporus contribute to the eutrophication of surface waters (Danalewich et al., 1998). To control eutrophication, the USEPA has established water quality criteria for total phosphorus concentration for lakes and streams (US EPA, 1976; Schindler, 1977). In addition, drinking water standards have also been set for nitrate nitrogen (NO_3-N) to prevent methemoglobinemia in infants, a potentially lethal condition known as blue baby syndrome (USEPA, 1976; Knobeloch et al., 2000). An estimated 25% of pesticide use in the United States results from nonagricultural pest control (Aspelin, 1998). Surface waters of urban watersheds have been found to contain pesticides associated with the turfgrass industry (Cohen et al., 1999; Gilliom et al., 2006). Examples include spring and summer detections of carbaryl and diazinon at levels that exceeded criteria for protection of aquatic life, and reports of 2,4-D, dicamba, and mecoprop in 85% of evaluated storm runoff events (Hoffman et al., 2000; Wotzka et al., 1994; USEPA, 1999). The objective of this study was to evaluate the off-site transport and impact of a fungicide and fertilizer with runoff from creeping bentgrass turf managed as a golf course fairway. Specific objectives included: (i) measuring runoff volumes and concentrations of flutolanil, soluble phosphorus (sol-P), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) in edge-of-turf runoff; (ii) calculating environmental concentrations anticipated to occur in a body of water receiving the runoff; and (iii) comparing measured and estimated concentrations of the chemicals of interest in runoff and a receiving surface water with toxicological endpoints or water quality standards.

MATERIALS AND METHODS

The described research was conducted as part of a multi-state collaborative effort to obtain standardized regional data on the fate and transport of turf protection products. As a result the construction and use of a rainfall simulator, timing of chemical application to initiation of simulated precipitation, and runoff collection followed a specific protocol. Fertilizer, a conservative tracer, and pesticides were applied to each turf plot following aerification and prior to initiation of rainfall simulation and the generation of runoff. Runoff, fertilizer and fungicide data are reported here.

Site description.

Runoff water was collected from turf plots managed as a golf course fairway on a study site located at the University of Minnesota Turf Research, Outreach and Education Center, Saint Paul, Minnesota. This 976 m^2 site comprised of Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed superactive, mesic Typic Hapludolls) with 3% organic carbon, 29% sand, 55% silt, and 16% clay. A natural slope running east to west was graded to 4% with less than 1% slope from north to south and sodded with 'L-93' creeping bentgrass 14 months prior to initiation of the reported runoff studies. The site was divided into 6 plots (24.4 m x 6.1 m, length x width) prepared in an east to west direction.

Runoff collection systems were constructed at the western edge of each plot similar to Cole et al. (1997). Stainless-steal flashing guided the runoff from the turf into 6.1-m gutters; constructed of 15.2-cm schedule 40 polyvinyl chloride (PVC) pipe that was cut in half length wise. Two 3.0-m long horizontally-split PVC pipes were joined in the center with a PVC-T (15.2 cm x 15.2 cm x 15.2 cm) which lead to a stainless steel LG 60° V trapezoidal flume (Plasti-Fab, Tualatin, OR) equipped with a bubble tube port and 2 sample collection ports. The runoff collection gutter and trapezoidal flume were placed in sand-filled trenches, which supported the gutter at a ≤ 2% slope while maintaining level conditions for the flume. This was done to encourage water flow and negate friction effects in the gutters while providing a level water height in the flume for accurate measurement of runoff volume and flow rates. Polyester landscape cloth covered the soil under the metal flashing and the banks of the trenches to maintain soil structure. Metal flashings were held in place with large nails. Paraffin wax provided a water tight seal between the turf edge and metal flashing. The alignment and integrity of the runoff collection systems were assessed each spring and prior to simulated precipitation events. Metal gutter covers and wooden flume shields prevented dilution of runoff with precipitation. Plots were hydrologically isolated with removable berms, constructed from horizontally-split 10.2-cm schedule 40 PVC pipe that were inverted to rest on the cut edges. Observation of water flow during runoff events showed no water movement under the PVC berms.

Management practices.

The turf was managed as a fairway with 1.25 cm height of cut (3 times weekly, clippings removed), top dressed with sand (weekly, 1.6 mm depth) and irrigated to prevent drought stress. The quantity of water applied with the maintenance irrigation was not enough to produce surface runoff.

Plots were aerated twice during each season (Table 1). In 2005, three of the six plots were aerated with hollow tines (HT: 0.95 cm internal diameter x 11.43 cm depth with 5 cm x 5 cm spacing) while the remaining plots were aerated using solid tines (ST: 0.95 cm diameter x 11.43 cm depth with 5 cm x 5 cm spacing) (Ryan Greensaire II Aerator, Ryan, Inc., Barrington, IL). Cores removed with the HT were allowed to dry, broken into smaller pieces, and worked back into the turf. A back-pack blower and leaf rake removed the turf and thatch from the plot surface. Plots were managed with the same type of aerification for both events (HT received HT, ST received ST), which were separated by 14 weeks (21 June 2005 and 27 Sep. 2005). The following year all six plots were aerated with HT (4 Aug. 2006). Forty-six days later all plots were aerated with HT for a second time (19 Sep. 2006). Plots receiving ST aerification in 2005 were further managed with vertical mowing (VM: 1 mm blades, 3.8 cm spacing, 1.9 cm depth; Turfco Triwave Seeder, Turfco Manufacturing, Inc., Blaine, MN) (26 Sep. 2006) following the second HT aerification. This manuscript reports observations recorded from the HT plots for 2005 (23 Aug 2005 (HT), 30 Sep 2005 (HT-HT)) and 2006 (15 Aug 2006 (HT-HT), 4 Oct 2006 (HT-HT)) and 3 additional plots that received HT aerification in 2006 following ST aerification in 2005 (15 Aug 2006 (ST-HT)). Runoff and chemical transport in runoff from plots managed with ST (ST and ST-ST) or HT-VM will be presented elsewhere.

Chemical application.

Plant Nutrient 18-3-18 (Agriliance LLC, Inver Grove Heights, MN) containing 18% nitrogen (9.72% urea nitrogen, 0.63% ammoniacal nitrogen, 3.15% water insoluble nitrogen, 4.50% methylene urea), 3% available phosphate (P_2O_5), and 18% soluble potash (K_2O) was applied to all plots perpendicular to runoff flow at a rate of 136.5 kg ha^{-1} 18-3-18 (24.4 kg N ha^{-1}, 1.8 kg P ha^{-1}). The granular fertilizer was applied first, followed by brief irrigation (< 1 mm) with the maintenance irrigation system, then application of a conservative tracer (potassium bromide), followed by a tank mix of commercially available pesticides. Pesticide formulations included ProStar® 70WP fungicide (Chipco® Professional Products, Aventis CropScience, Research Triangle Park, NC) containing 70% flutolanil, Dursban® 50W insecticide (Dow AgroSciences LLC, Indianapolis, IN) containing 50% chlorpyrifos (O,O-diethyl O-(3,5,6-trichloro-2-pyridinyl) phosphorothioate), and Trimec® Bentgrass Formula herbicide (PBI Gordon, Kansas City, MO) containing 9.92% Mecoprop-p (dimethylamine salt of (+)-(R)-2-(2-methyl-4-chlorophenoxy) propionic acid), 6.12% 2,4-D (dimethylamine salt of 2,4-dichlorophenoxyacetic acid), and 2.53% dicamba (dimethylamine salt of 3,6-dichloro-o-anisic acid). The tracer and pesticides were applied to all plots perpendicular to runoff flow, at a speed of 3.2 kmph from a 4.6 m spray boom fitted with TeeJet XR8004 nozzles (TeeJet Technologies, Wheaton, IL) spaced 50.8 cm apart with a sprayer pressure of 138 kPa. No additional irrigation or precipitation occurred between completion of chemical application and initiation of simulated precipitation. All chemicals were applied at label rates 26 ± 13 h prior to initiation of each rainfall simulation. The insecticide (chlorpyrifos), herbicides (Mecoprop-p, dicamba and 2,4-D) and tracer (potassium bromide) data will be presented elsewhere. Nutrient (soluble phosphorus (sol-P), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N)) and fungicide (flutolanil) transport are reported herein.

Simulated precipitation.

A rainfall simulator was constructed based on U.S. patent 5,279,151 (Coody and Lawrence, 1994), which was designed to deliver precipitation having a droplet size spectrum, impact velocity, spatial uniformity and intensity similar to natural precipitation. The simulator delivered precipitation to two 24.4 m x 6.1 m plots simultaneously a rate of 35.6 mm h^{-1}; a rate similar to storm intensities recorded in Minnesota, USA, during July through October. Five cm dia. schedule 40 PVC pipe functioned as the base of the simulator which guided water to eighteen 2.54-cm schedule 40 PVC risers each fitted with a pressure regulator (Lo-Flo, 15 psi) and a nozzle (#25) containing a standard PC-S3000 spinner (Nelson Irrigation, Walla Walla, WA). Risers were spaced 3.7 m apart with nozzles and spinners suspended 2.7 m above the turf.

Forty-eight hours prior to initiation of simulated precipitation, each plot was pre-wetted with the maintenance irrigation system beyond soil saturation (volumetric water content: 68 ± 3 %) to ensure uniform water distribution and allow for collection of background samples. Irrigation water samples and resulting background runoff were collected for analysis. The following day the turf was mowed (1.25 cm height, clippings removed) and runoff collection gutters and flumes were cleaned and covered with plastic sheeting to prevent contamination during chemical application. Prior to each application, Petri dishes (glass, 14-cm) were distributed across the plots to verify chemical delivery and determine application rates. Plastic sheeting and Petri dishes were removed following chemical application and 12-cm rain gauges (Taylor Precision Products, Oak Brook, IL) were distributed throughout each plot to quantify simulated precipitation. Soil moisture was measured in a grid pattern (at 1.5, 3.1, 4.6 mnorth to south by 3.1, 12.2, 21.3 m west to east, n=9) to a depth of 12 cm with a soil moisture meter (Field Scout TDR 300, Spectrum Technologies) prior to and following simulated precipitation. Simulated precipitation was initiated once wind speeds dropped below 2 m s^{-1} (average wind speed during simulation = 0.8 ± 0.7 m s^{-1}) (Davis Instruments, Hayward, CA) and continued until 90 minutes of runoff had been generated from each plot. Runoff collection was completed 138 ± 4 min following initiation of precipitation (Table 1).

Runoff collection and analysis.

An automated flow meter (Isco model 730, Lincoln, NE) and runoff sampler containing 24, 350-mL glass bottles (ISCO model 6700, Lincoln, NE) measured flow rates, recorded runoff volume and collected time-paced (5 min) runoff samples from each plot. Instrumentation was calibrated each

Table 1. Time line of aerification, chemical application, simulation of precipitation and collection of runoff.

aerification designation†		date (day-month-year)				precipitation		
plots 2, 4, 5	plots 1, 3, 6	aerification	chemical application‡	precipitation/runoff	DAA§	total applied (mm)	duration (min)	rate (mm hr^{-1})
HT¶	ST	21-Jun-05	22-Aug-2005	23-Aug-2005	63	59 ± 5	105 ± 2	34 ± 3
HT-HT	ST-ST	27-Sep-05	29-Sep-2005	30-Sep-2005	2	45 ± 8	113 ± 9	24 ± 4
HT-HT	**ST-HT**	4-Aug-2006	14-Aug-2006	15-Aug-2006	11	71 ± 8	121 ± 6	35 ± 3
HT-HT	HT-VM	9/19/2006 (HT) 9/26/2006 (VM)	4-Oct-2006	4-Oct-2006	15 8	75 ± 7	120 ± 7	37 ± 2

†Hollow (HT) or solid (ST) tines: 0.95 cm diameter x 11.43 cm depth, 5 x 5 cm spacing; Vertical mowing (VM: 1 mm blades, 3.8 cm spacing, 1.9 cm depth). The aerification designation displays historical and current aerification. For example ST-HT plots were managed with ST in 2005 and managed with HT in 2006 prior to the 15-Aug-2006 runoff event.

‡Plant Nutrient 18-3-18® and ProStar® 70WP fungicide applied at label rates 22 ± 10 h prior to initiation of simulated precipitation.

§DAA = days after aerification (days between last aerification and initiation of simulated precipitation and runoff).

¶Bold text represents the plots and aerification practices discussed in this manuscript.

spring and immediately prior to simulated precipitation events. Water samples were removed from the automated samplers, divided into nutrient and fungicide sub-samples and stored at -20°C until laboratory analysis. Irrigation source water, background runoff water, and background runoff spiked with fertilizer granules or flutolanil served as blank and positive control samples. Water samples were analyzed for soluble phosphorus (sol-P), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N) and flutolanil. Soluble P was quantified from filtered (0.45 μm) water samples following standard methodologies for molybdenum blue reaction and spectrophotometric quantification [Murphy and Riley, 1962; Self-Davis et al., 2000]. Levels of NH_4-N and NO_3-N were determined by the diffusion-conductivity method involving the gaseous diffusion of ammonia (NH_3) across a gas permeable membrane in the presence of excess potassium hydroxide (KOH) with subsequent conductivity detection [Carlson et al., 1990]. Flutolanil was quantified from runoff samples (3 mL) filtered through a 0.45 μm nylon syringe filter (Whatman Inc, Clifton, NJ) followed by methanol (0.5 ml) to rinse the filter. Concentrations of flutolanil were measured by direct injection of 500 μl of the filtered sample and rinsate onto a high performance liquid chromatograph (Waters model 717plus autosampler and model 1525 binary pump) with a photodiode array detector (Waters model 2996: Waters, Milford, MA) set at 230nm. Two solvents [solvent A: laboratory-grade organic-free water (0.17% trifluoroacetic acid); solvent B: 82:18 methanol:acetonitrile] were employed to elute the analytes from a 150 mm long, 4.6 mm diameter C-18 column with 5 μm packing (Agilent, New Castle, DE) at a rate of 1 ml min^{-1}. Initial conditions, 60% B, were held for 2 minutes followed by a gradient ramped from 60% to 95% B in 23 min, a 3 minute hold, then back to 60% B in 10 min with a 5 minute hold. Limits of quantification for flutolanil were 4.5 ± 0.8 μg L^{-1} and recoveries were 91 ± 8%.

Calculation of edge-of-plot loads and concentrations in receiving surface waters.

Nutrient and fungicide loads (mg m^{-2}) from edge-of-plot runoff were calculated from recorded runoff volumes (L m^{-2}) and measured concentrations (mg L^{-1}) of sol-P, NH_4-N, NO_3-N, flutolanil in the runoff. Concentrations of chemicals in a body of water receiving the runoff was determined according to the scenario utilized in the Exposure Analysis Modeling System (EXAMS) model were runoff from a 10-ha (100,000 m^2) area drains into a pond with 1-ha (10,000 m^2) surface area and 2-m depth (www.epa.gov/oppefed1/models/water). This was accomplished by calculating the average nutrient and fungicide loads for the five reported runoff events then extrapolating to determine the load from a 10-ha area. The total mass for each chemical of interest was then divided by the total volume of the theoretical pond to give the estimated environmental concentration (EEC), which can be compared to water quality criteria, drinking water standards or toxicity endpoints to estimate risk and impact.

Statistical analysis.

Completely randomized analysis of variance (ANOVA) was performed comparing the percent of applied precipitation resulting as runoff and the percent of applied chemicals transported in runoff for all runoff events. A significant F ($P = 0.05$) implied a significant difference among treatment means. Correlation coefficients were calculated to assess the association of runoff volume and chemical concentration with chemical load (Steel and Torrie, 1997).

RESULTS AND DISCUSSION

Simulated precipitation and runoff volumes.

Simulated precipitation events were performed during the 2005 and 2006 seasons. In each event precipitation was terminated 90 minutes following the onset of runoff. Measured coefficient of uniformity for the rainfall simulator was 82 to 84%. Rain gauges distributed throughout the plots (n=36) measured rainfall rates of 24 ± 4 mm h^{-1} (mean ± standard deviation) to 37 ± 2 mm h^{-1} for a total of 45 ± 8 mm to 75 ± 7 mm of precipitation. Variations in generated rainfall rates for the simulation events were most likely the result of changes in pressure at the water source during the time of simulated precipitation. Precipitation-quantity, -rates, and -durations are provided in Table 1.

Precipitation and collection of runoff was initiated 2, 11, 15, and 63 d following aerification. Volumetric soil moistures measured < 2 h prior to initiation of precipitation and 48 h post-saturation were 45 ± 4 % with post-simulation (< 3 h) moisture measurements of 68 ± 3%. Runoff was first observed 22 ± 7 min following the initiation of precipitation (Fig. 1). Steady-state runoff rates were observed for 56 ± 9 min beginning approximately 60 min after the initiation of precipitation with average flow rates of 22 ± 6 L min^{-1} and maximum flow rates of 43 ± 9 L min^{-1}. Cumulative runoff volumes reported for each event are as follows: 23 Aug 2005 (HT) = 3,149 ± 932 L; 30 Sep 2005 (HT-HT) = 1,856 ± 139 L; 15 Aug 2006 (HT-HT) = 3,964 ± 168 L, 15 Aug 2006 (ST-HT) = 3,279 ± 1,333 L; and 4 Oct 2006 (HT-HT) = 3,843 ± 130 L. Runoff collected from turf plots 2, 11, 11, 15, and 63d following HT aerification

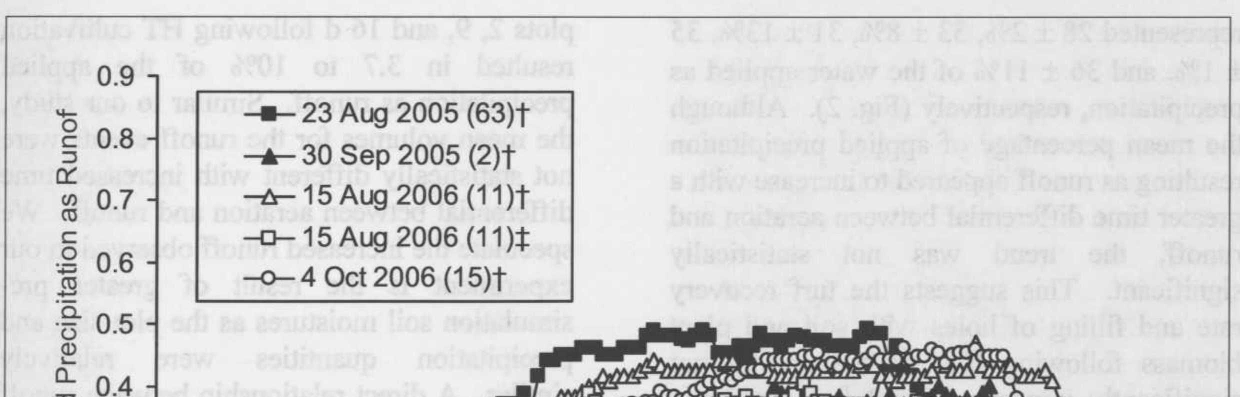

Fig. 1. Runoff hydrographs from creeping bentgrass turf managed as a golf course fairway. Numbers displayed parenthetically represent days between hollow tine aerification and runoff. † = plots managed with hollow tine aerification in 2005 (HT and HT-HT) and 2006 (HT-HT). ‡ = plots managed with solid tine aerification in 2005 and hollow tine aerification in 2006 (ST-HT).

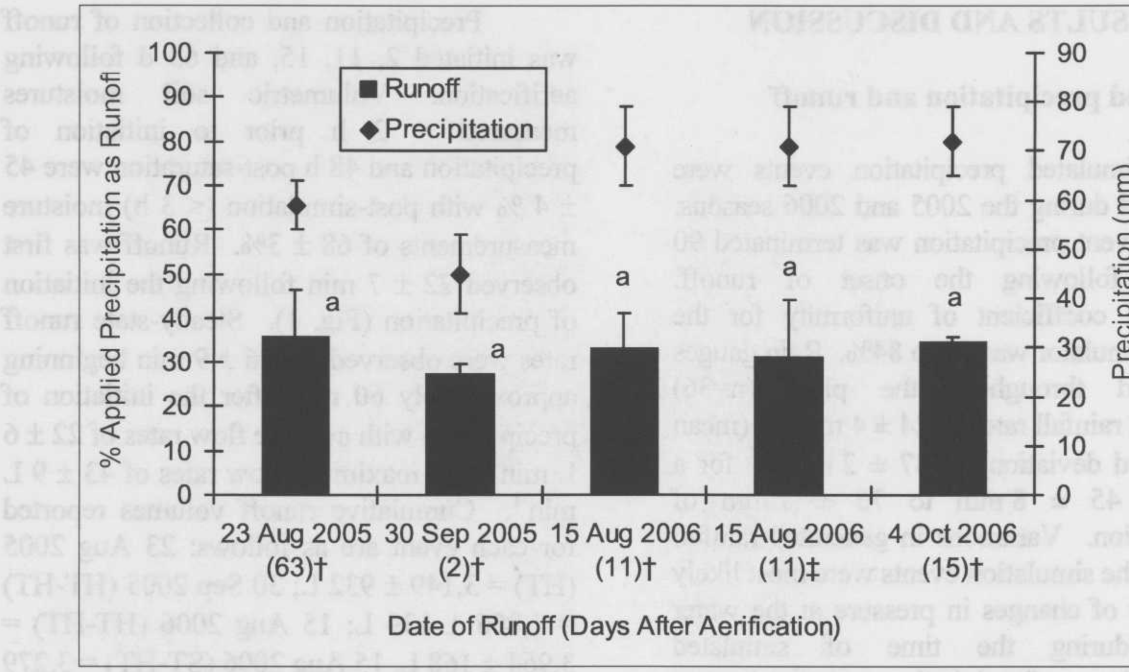

Fig. 2. Precipitation and percent of precipitiation resulting as runoff from creeping bentgrass turf managed as a golf course fairway. Error bars represent standard deviation of the means. Means followed by a different letter are significantly different ($P \leq 0.05$). † = plots managed with hollow tine aerification in 2005 (HT and HT-HT) and 2006 (HT-HT). ‡ = plots managed with solid tine aerification in 2005 and hollow tine aerification in 2006 (ST-HT).

represented 28 ± 2%, 33 ± 8%, 31 ± 13%, 35 ± 1%, and 36 ± 11% of the water applied as precipitation, respectively (Fig. 2). Although the mean percentage of applied precipitation resulting as runoff appeared to increase with a greater time differential between aeration and runoff, the trend was not statistically significant. This suggests the turf recovery rate and filling of holes with soil and plant biomass following HT aerification did not significantly impact overland flow volumes. Shuman (2002) observed 37 to 44% of applied water as runoff from fairways of 'Tifway' bermudagrass (*Cynodon dactylon* (L.) Pers.) that received 50 mm of simulated precipitation 2 d following irrigation to field capacity. This is in range of our observations though core cultivation was not reported in their study. We observed a larger percentage of runoff and increased time to runoff relative to the study of Kauffman and Watschke (2007) where 25 min of simulated rainfall (152 mm h^{-1}) applied to creeping bentgrass plots 2, 9, and 16 d following HT cultivation resulted in 3.7 to 10% of the applied precipitation as runoff. Similar to our study, the mean volumes for the runoff events were not statistically different with increased time differential between aeration and runoff. We speculate the increased runoff observed in our experiment is the result of greater pre-simulation soil moistures as the plot size and precipitation quantities were relatively similar. A direct relationship between runoff volume and soil moisture at the time of the precipitation event has been reported (Shuman 2002). The delay in time to runoff observed in our study compared to the study of Kauffman and Watschke (2007) is most likely the result of a more gradual plot slope (4% rather than 9-11%), lesser precipitation rates (24-37 mm h^{-1} rather than 152 mm h^{-1}), and removal of deeper and more closely spaced cores (depth x spacing x diameter: 11.43 cm x 5 cm x 0.95 cm rather than 3.8 cm x 6.4 cm x 1.6 cm).

Fungicide and nutrient concentrations in runoff.

Analysis of the source water applied as maintenance irrigation and simulated precipitation contained no residues of flutolanil and negligible levels of nutrients (sol-P, NH_4-N and NO_3-N = 0.001 to 0.005 mg L^{-1}). All chemicals of interest were detected in the initial runoff samples and throughout the runoff events (Fig. 3). Average (avg.) and maximum (max.) concentrations measured in the runoff for the five evaluated events were as follows: sol-P = 0.69 ± 0.18 mg L^{-1} (avg.), 1.30 mg L^{-1} (max.); NH_4-N = 0.84 ± 0.23 mg L^{-1} (avg.), 3.68 mg L^{-1} (max.); NO_3-N = 0.23 ± 0.06 mg L^{-1} (avg.), 0.57 mg L^{-1} (max.); flutolanil = 1.10 ± 0.18 mg L^{-1} (avg.), 1.64 mg L^{-1} (max.). Our edge-of-plot runoff contained phosphorus concentrations that were 7 to 26 times greater than USEPA water quality criteria to limit eutrophication (total phosphorus 0.05 mg L^{-1} within a lake or reservoir, 0.1 mg L^{-1} in streams) (USEPA, 1976; Schindler, 1977). Concentrations of NO_3-N were below the drinking water standard (10 mg L^{-1} NO_3-N) [USEPA, 1976; Knobeloch et al., 2000] which is consistent with the findings of other turf runoff studies (Linde and Watschke, 1997; Linde et al.,1994; Gross et al., 1990). Residues of flutolanil measured in the runoff were greater than the median lethal concentration (LC50); or the concentration of compound that results in mortality of fifty percent of the exposed organisms during a measured exposure period, for a salt-water crustacean (*Americamysis bahia* (shrimp), 4 d LC50 = 0.13 mg L^{-1}). Concentrations of flutolanil in the runoff were below the LC50 for a salt-water mollusc (*Crassostrea virginica*

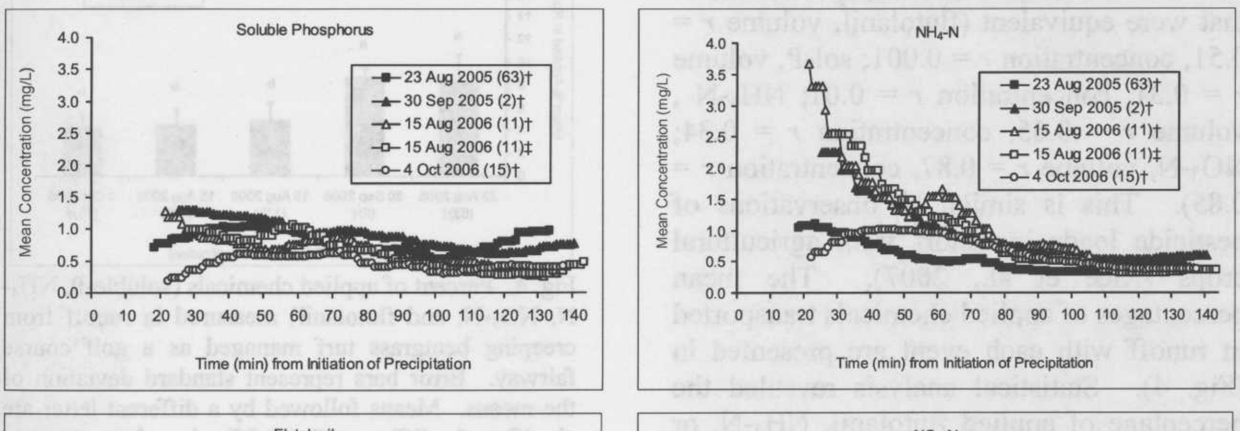

Fig. 3. Mean concentration of soluble-P, NH_4-N, NO_3-N, and flutolanil measured in runoff from creeping bentgrass turf managed as a golf course fairway. † = plots managed with hollow tine aerification in 2005 (HT and HT-HT) and 2006 (HT-HT). ‡ = plots managed with solid tine aerification in 2005 and hollow tine aerification in 2006 (ST-HT).

(oyster), 4 d LC50 = 1.5 mg L^{-1}), fresh-water fish (*Lepomis Macrochirus* (bluegill) and *Oncorhynchus Mykiss* (rainbow trout), 4 d LC50 = 5.4 to 10 mg L^{-1}), a fresh-water crustacean (*Procambarus Clarkii* (crayfish), 4 d LC50 = 6 mg L^{-1}) and fresh-water amphibians (*Rana brevipoda porosa* (frog), 2 d LC50 = 10 to 100 mg L^{-1}; *Bufo bufo japonicus* (toad), 2 d LC50 = 13 mg L^{-1}) (USEPA, 2008).

When overland flow volumes and plot size were considered, the average mass of chemicals transported with runoff for all events were 13.56 ± 2.86 mg m^{-2} sol-P, 15.65 ± 5.91 mg m^{-2} NH_4-N, 4.84 ± 2.56 mg m^{-2} NO_3-N, and 23.27 ± 7.39 mg m^{-2} flutolanil. Correlation analysis of chemical loads with runoff volumes and chemical concentrations revealed loads were more associated with runoff volume than chemical concentrations, with the exception of NO_3-N that were equivalent (flutolanil, volume r = 0.51, concentration r = 0.001; sol-P, volume r = 0.31, concentration r = 0.01; NH_4-N, volume r = 0.65, concentration r = 0.34; NO_3-N, volume r = 0.87, concentration r = 0.85). This is similar to observations of pesticide loads in runoff from agricultural crops (Rice et al., 2007). The mean percentages of applied chemicals transported in runoff with each event are presented in (Fig. 4). Statistical analysis revealed the percentage of applied flutolanil, NH_4-N, or NO_3-N transported in runoff was similar regardless of the time differential between HT aerification and runoff (2, 11, 15, or 63 d), the date the runoff was collection (2005 or 2006, mid Aug. to early Oct.) or the management history of the plots (HT, HT-HT or ST-HT). The average percentage of applied chemical transported in runoff for the 5 runoff events was 5.9 ± 1.4 % for flutolanil, 7.6 ± 2.3 % for NH_4-N, and 8.3 ± 1.7 % for NO_3-N. For sol-P the percentage of applied transported in runoff was

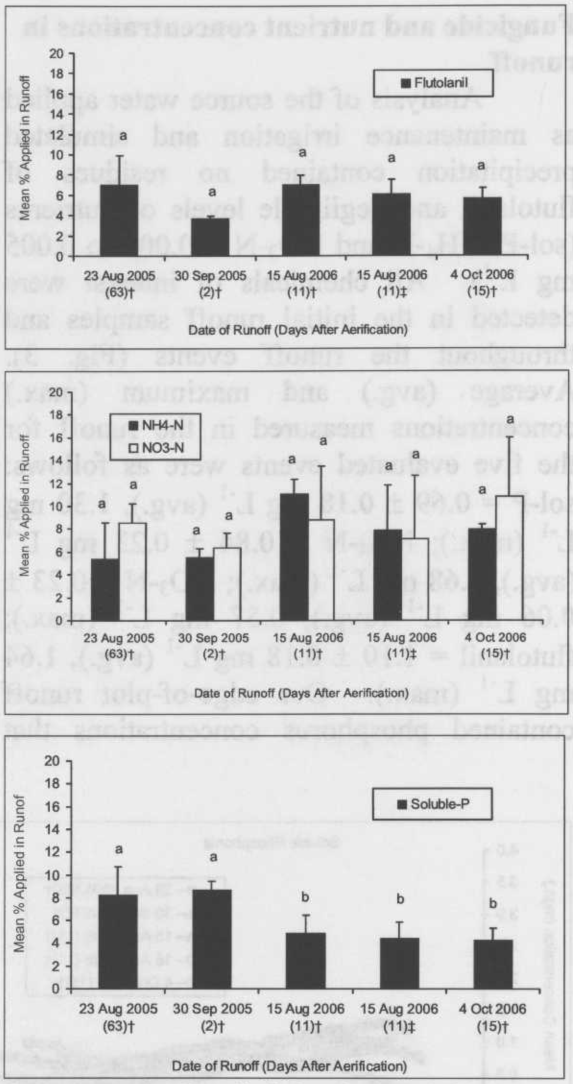

Fig. 4. Percent of applied chemicals (soluble-P, NH_4-N, NO_3-N, and flutolanil) measured in runoff from creeping bentgrass turf managed as a golf course fairway. Error bars represent standard deviation of the means. Means followed by a different letter are significantly different ($P \leq 0.05$). † = plots managed with hollow tine aerification in 2005 (HT and HT-HT) and 2006 (HT-HT). ‡ = plots managed with solid tine aerification in 2005 and hollow tine aerification in 2006 (ST-HT).

statistically different in 2005 (8.5 ± 0.3 %) compared to 2006 (4.5 ± 0.4 %). Closer observation of the individual runoff events revealed this difference was not the result of the time differential between HT aerification or the month of runoff collection as there was no statistical difference between runoff events occurring within the same year (Fig. 4). For all runoff events the turf was actively growing (mean air temperatures: 2005: 1-31 Aug. (71°F), 1-30 Sep. (67°F); 2006: 1-31 Aug. 2006 (72°F), 1-30 Sep. (60°F), 4 Oct. (54°F). Additional evaluation of thatch, turf, and soil samples will be required to fully explain the divergence observed in sol-P in runoff from 2005 and 2006.

Overall, less than 10% of the applied nutrients and fungicide were measured in the runoff from our turf plots. This is in range with observations reported by other researchers. Linde and Watschke (1997) measured 11% of applied phosphorus and 2% of applied nitrogen in runoff from creeping bentgrass and perennial ryegrass 8 h after fertilization. Shuman (2002) observed 10% of applied phosphorus and less than one percent of applied NO_3-N was found in the first runoff event occurring 4 h after application to simulated golf course fairways of bermudagrass. Cole et al. (1997) reported less than one to 10% of applied nutrients and less than 3% to 15% of applied pesticides (2,4-D, mecoprop and dicamba) were transported in runoff from bermudagrass turf depending on the amount of precipitation, soil moisture, and management. This concurs with the findings of Ma et al. (1999) where runoff from bermudagrass plots managed as a fairway contained 9, 10, and 15% of applied 2,4-D, mecoprop, and dicamba, respectively. Smaller quantities (less than 3%) of imidacloprid, 2,4-D, cyanazine, and sulfometuronmethyl were reported in the studies of Armbrust and Peeler (2002) and Wauchope et al. (1990).

Chemical concentrations in a body of water receiving surface runoff.

Estimation of environmental concentrations in the receiving surface water (runoff from 10-ha area into a 1-ha surface area x 2-m depth) resulted in 0.07 mg L^{-1} sol-P, 0.08 mg L^{-1} NH_4-N, 0.02 mg L^{-1} NO_3-N, and 0.12 mg L^{-1} flutolanil. After dilution, phosphorus concentrations remained above levels associated with increased algal growth (0.025 mg L^{-1}) and the USEPA water quality criteria to limit eutrophication in lakes and reservoirs (0.05 mg L^{-1}). Nitrogen concentrations were an order of magnitude below levels associated with increased algal growth (1 mg L^{-1}) and 500 times below the drinking water standard for NO_3-N (10 mg L^{-1}) (USEPA, 1976; Schindler, 1977; Walker and Branham, 1992; Knobeloch et al., 2000). Levels of flutolanil in the receiving surface were all below the LC50 (0.13 to 100 mg L^{-1}) for the 7 aquatic organisms evaluated; representing amphibians (frog, toad), crustaceans (shrimp, crayfish), fish (bluegill, rainbow trout), and a mollusc (oyster).

As efforts to ban or restrict the use of chemicals on residential turf are proposed and enforced (Rosen and Horgan, 2005; Vavrek, 2005; Krueger, 2006; Huber, 2008) quantitative information on the off-site transport of chemicals with runoff will be valuable in providing scientifically-based data for making informed decisions. Runoff and chemical data collected from this study can be utilized to evaluate predictive runoff transport models (Haith, 2001; Haith and Rossi, 2003; Kramer et al., 2009) and to assess non-point source pollution potential and risk of pesticides and nutrients transported in runoff from turf. Greater knowledge of chemical fate and associated risk will allow for modified or restricted use of fertilizers and pesticides were hazard potential has been demonstrated while maintaining the use of these products as tools for managing turf where a plausible risk is unproven.

CONCLUSIONS

Runoff from managed turf may contain pesticides and nutrients that contribute to contamination of receiving surface waters. In this study we observed that 4.5 to 8.5 % of applied NH_4-N, NO_3-N, sol-P, and flutolanil were measured in edge-of-plot runoff when fertilizer and a fungicide were applied at label rates to creeping bentgrass fairway turf, 26 ± 13 h prior to simulated precipitation (45 to 75 mm). Time differential between HT aerification and runoff (2 to 63 d) did not significantly influence the percentage of applied chemicals transported in the runoff. All chemicals of interest were detected in the initial runoff samples and throughout the runoff events with average concentrations of 1.10, 0.69, 0.84, and 0.23 mg L^{-1} for flutolanil, sol-P, NH_4-N, and NO_3-N, respectively. The edge-of-plot runoff contained concentrations of NO_3-N that were less than the drinking water standard, levels of flutolanil that were below the LC50 for 6 of 7 aquatic organisms assessed, and phosphorus concentrations above the USEPA water quality criteria to limit eutrophication. Estimated environmental concentrations of the chemicals of interest were calaculated based on the dilution of runoff when entering a receiving body of water (runoff from 10-ha area into a 1-ha surface area x 2-m depth). Concentrations of flutolanil, NH_4-N, and NO_3-N were below the evaluated levels of concern while sol-P remained above concentrations associated with increased algal growth and eutrophication.

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