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Evaluation of individual and combined management practices to reduce the off-site transport of pesticides from golf course turf☆

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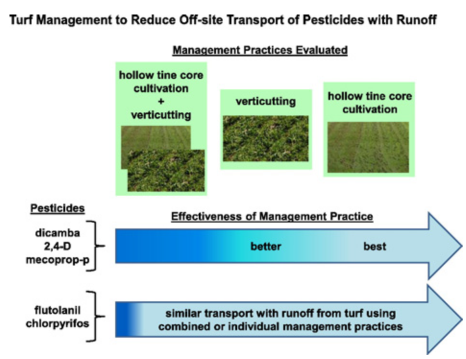
HIGHLIGHTS

- Evaluated runoff from turf managed with verticutting followed by core cultivation
- First research on pesticide transport with turf runoff for these combined practices
- Pesticides of greater water solubility: Increased transport from combined practices
- Pesticides of low water solubility: Similar transport combined or separate practice
- Important to turfgrass industry (golf, sports, parks) for environmental stewardship

GRAPHICAL ABSTRACT



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ABSTRACT

The detection of pesticides, associated with turfgrass management, in storm runoff and surface waters of urban watersheds has raised concerns regarding their source, potential environmental effects and a need for strategies to reduce their inputs. In previous research we discovered that hollow tine core cultivation (HTCC) was more effective than other management practices for reducing the off-site transport of pesticides with runoff from creeping bentgrass turf managed as a golf course fairway. This was primarily the result of enhanced infiltration and reduced runoff volumes associated with turf managed with hollow tines. In this study we evaluated the addition of verticutting (VC) to HTCC (HTCC + VC) in an attempt to further enhance infiltration and mitigate the off-site transport of pesticides with runoff from managed turf. Overall, greater or equal quantities of pesticides were transported with runoff from plots managed with HTCC + VC compared to HTCC or VC alone. For the pesticides evaluated HTCC < VC < HTCC + VC for the off-site transport of the high mobility pesticides while HTCC = VC = HTCC + VC for the low mobility pesticides. It is likely the addition of VC following HTCC further increased compaction and reduced availability of recently exposed soil sorptive sites produced from the HTCC. Results of this research provides guidance to golf course managers on selection of management practices that assure quality turf while minimizing off-site transport of pesticides, improving pesticide efficacy and the environmental stewardship of managed biological systems.

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Abbreviations: HTCC, hollow tine core cultivation; HTCC + VC, hollow tine core cultivation with verticutting; MCPP, mecoprop-p; VC, verticutting; 2,4-D, 2,4-dichlorophenoxyacetic acid.

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1. Introduction

Managed turf is found in commercial, public and private localities; on athletic fields and golf courses, as sod farms, in parks and cemeteries, along roadsides, and as commercial and residential lawns. Ecosystem services offered by managed turf include habitat for wildlife and an influence on human longevity, as long-term exposure to residential green spaces is associated with reduced risk of cardiovascular disease mortality (Gascon et al., 2016).

There are >32,000 golf courses located throughout the world (Saito, 2010; World Golf, 2016; World Golf Foundation, 2016). Golf courses contain some of the most intensely managed turf; often requiring applications of pesticides (GCSSA, 2012) at rates that may exceed those typically found in agricultural or home environments (Barbash and Resek, 1996; Gianessi and Anderson, 1996; Smith and Bridges, 1996). Pest control of turfgrass account for a significant portion of the urban/suburban pesticide market, historically representing 500 to 700 million dollars of billion dollar annual sales in the United States in the late 1990's (Joyce, 1998; Racke, 2000; Clark and Kenna, 2001). In 2007, world pesticide expenditures represented >39 billion dollars with the United States contributing to 33% of the world market. Sales statistics in the United States revealed 13% of pesticide usage occurred in the industrial, commercial and governmental sectors while 9% represented the home and garden sectors (Grube et al., 2011).

Pesticides are biologically active compounds designed to interfere with metabolic processes (Matsumura, 1985; Manahan, 1994). Therefore the detection of pesticide residues beyond their area of application (Hoffman et al., 2000; Goel et al., 2005; Harman-Fetcho et al., 2005; Loague and Soutter, 2006; Hayward et al., 2010; Lv et al., 2010; Riederer et al., 2010; Weber et al., 2010; Slavens and Petrovic, 2012; Wong and Haith, 2013) and reports of adverse effects of pesticides to non-target organisms at environmentally relevant levels (Chandler and Scott, 1991; Clark et al., 1993; Margni et al., 2002; Schulz, 2004) has invoked public concern. Across the globe researchers have detected multiple contaminants in storm runoff and surface waters (Cohen et al., 1999; Hoffman et al., 2000; Soulsby et al., 2004; Nash et al., 2005; Gilliom et al., 2006; Xu et al., 2007; Bakri et al., 2008; Silva et al., 2015; Fairbairn et al., 2016; Mekonen et al., 2016; Montuori et al., 2016). 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 residues of chlorpyrifos, diazinon and 2,4-dichlorophenoxyacetic acid (2,4-D) in surface waters throughout the year (Frick et al., 1998), spring and summer detections of diazinon and carbaryl in surface waters at levels that exceeded criteria for protection of aquatic life (Hoffman et al., 2000) and reports that 85% of evaluated storm runoff events contained dicamba, mecoprop and 2,4-D (Wotzka et al., 1994).

Green spaces are subject to foot and vehicle traffic; resulting in soil compaction, turf wear, and reduced infiltration of water (Baldwin et al., 2006). As turfgrass matures a loose organic layer of intermingled dead and living shoots, known as thatch, develop. An excessive thatch-mat has been shown to reduce water infiltration, decrease hydraulic conductivity, increase disease and pest pressure, and lessen cold temperature tolerance (Beard, 1973; White and Dickens, 1984; Murray and Juska, 1977; Harris, 1978; Miller, 1965). Researchers have evaluated management and cultural practices for turfgrass to assess their influence on stimulating root and shoot growth, controlling thatch, and alleviating surface compaction (Beard, 1973; White and Dickens, 1984; Turgeon, 1985; Carrow et al., 1987; Dunn et al., 1995; Callahan et al., 1998; Vargas and Turgeon, 2004; McCarty et al., 2005; McCarty et al., 2007; Barton et al., 2009; Rowland et al., 2009). Hollow tine core cultivation (HTCC) and verticutting (VC) are two important management practices used in the turf industry; particularly on golf courses and recreational fields and less frequently in parks or on large scale lawns (Murphy et al., 1992; Stier and Hollman, 2003; Torisello, 2007; Barton et al., 2009; Kitchen, 2014). For HTCC, cores are removed from the turf and allowed to air-dry on the turf surface before the soil is brushed back into the open holes and the extracted thatch is removed. In contrast, VC slices the turf with rotating blades that remove thatch and create rows for water to infiltrate as well as to prepare seedbeds for overseeding. Both management practices enhance water movement into the root zone; resulting in increased rainfall infiltration, greater rooting depth that lessens water leaching beyond the root zone, and healthier turf that requires less water and need for pest control (Waltz, 2007). Golf course managers, irrespective of climatologic conditions, implement these cultural practices multiple times each growing season (e.g. two to three times a year or as often as every 10 days).

Studies have been done to evaluate nutrient and pesticide vertical transport in turfgrass with leachate, and the potential of aeration to enhance preferential flow and plant uptake of pesticides (Liu et al., 1995; Smith and Bridges, 1996; Starrett et al., 1996; Gardner et al., 2000; Nektarios et al., 2007; Slavens and Petrovic, 2012). Turfgrass runoff has also been evaluated for nutrient and pesticide concentrations to determine the influence of commercial product formulation, active ingredient physical-chemical properties, irrigation practices, grass cover and buffers, and core cultivation or verticutting on their off-site transport with overland flow (Wauchope et al., 1990; Cole et al., 1997; Evans et al., 1998; Kauffman and Watschke, 2007; Moss et al., 2007; Rice et al., 2010a; Rice et al., 2010b; Rice and Horgan, 2011; Rice et al., 2011; Slavens and Petrovic, 2012). Recently Jeffries et al. (2016) explored the use of verticutting alone and in combination with scalping or activated charcoal to improve overseeding establishment of perennial ryegrass following indaziflam treatment to control undesired broadleaf plants in turfgrass systems.

A literature search shows the present study is the first research exploring the mitigation of pesticide transport with runoff from turfgrass using a combination of two management practices that mechanically enhance infiltration, HTCC and VC. Specific objectives were to quantify runoff volumes and the concentration of pesticides transported with runoff from fairway turf managed with HTCC combined with VC (HTCC + VC) compared to either of these management practices individually (HTCC or VC). Calculation of pesticide mass loads will reveal enhanced or reduced mitigation of the off-site transport of pesticides with runoff when using the combined management practices. Our research evaluating nutrient transport from HTCC + VC versus HTCC was previously published in this journal (Rice and Horgan, 2013).

2. Materials and methods

2.1. Site description

Runoff data were collected from turf plots managed as a golf course fairway located at the University of Minnesota Turf Research, Outreach and Education Center, St. Paul, Minnesota, USA. The soil consisted 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 that was covered with *Agrostis palustris* Huds. (L-93 creeping bentgrass). The 976 m^2 site was divided into six plots with each plot measuring 24.4 m length × 6.1 m width.

2.2. Collection of runoff

Runoff collection systems were constructed at the western end of each plot, modified from the design of Cole et al. (1997) and pictured in a previous publication of this journal (Rice and Horgan, 2017). Overall, runoff from the turf was guided by stainless steel flashing into polyvinyl chloride (PVC) gutters that led to stainless steel trapezoidal flume (Plasti-Fab, Tualatin, OR, USA) equipped with sample collection and bubble tube ports. Gutter hoods and flume shields prevented dilution of runoff with precipitation. Flow data and water samples were collected using flow meters (Isco model 730, Lincoln, NE, USA) and automated runoff samplers (ISCO model 6700) that deposited water samples into

Table 1
Pesticide physiochemical properties.[a]

Pesticide	Water solubility (20 °C) ($mg\ L^{-1}$)	K_{OC}[b] ($mL\ g^{-1}$)	K_{OW}[c] (pH 7, 20 °C) (Log P)	Half life (d) Water phase	Half life (d) Water-sediment	Half life (d) Soil
Chlorpyrifos[d]	1.05	8151	4.7	5	37	50
Flutolanil[e]	8.01	735	3.17	91	320	233
2,4-D[f]	23,180	56	−0.83	29	29	10
Dicamba[g]	250,000	12	−1.88	40	41	8
MCPP[h]	860	31	0.02	37	50	8

[a] http://sitem.herts.ac.uk/aeru/footprint/en/index.htm.
[b] Soil organic carbon partition coefficient.
[c] Octanol-water partition coefficient.
[d] Chlorpyrifos (*O,O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate).
[e] Flutolanil (*N*-[3-(1-methylethoxy) phenyl]-2-(trifluoromethyl) benzamide).
[f] 2,4-D (dimethylamine salt of 2,4-dichlorophenoxyacetic acid).
[g] Dicamba (dimethylamine salt of 3,6-dichloro-*o*-anisic acid).
[h] Mecoprop-P (dimethylamine salt of (+)-(*R*)-2-(2-methyl-4-chlorophenoxy) propionic acid).

24, 350-mL glass bottles per plot. Water samples were removed from the samplers and stored at −20 °C until laboratory processing and analysis.

2.3. Turf management

A. palustris was managed as a golf course fairway: height of cut 1.25 cm (3 times weekly, clippings removed), top dressed with sand (1.6 mm depth, weekly) and irrigated to prevent drought stress.

2.3.1. HTCC + VC versus HTCC

The runoff events were replicated in different years and performed while the turf was actively growing (runoff event-1: October 4–5, air temperatures max/min: 24 °C/11 °C; runoff event-2: August 11–12, air temperatures max/min: 31 °C/17 °C). Fifteen days (15 ± 1 d) prior to initiation of the runoff study (days before runoff (dbr)), all plots were aerated with hollow tines (0.95 cm internal diameter × 11.43 cm depth with 5 cm × 5 cm spacing) (Ryan Greensaire II Aerator, Ryan, Inc., Barrington, IL). Cores removed with the hollow tines were allowed to air dry then brushed back into the turf using a leaf rake and back-pack blower to remove turf and thatch from the plot surface. Seven days following hollow tine core cultivation (8 dbr), three of the six plots were verticut with 1 mm blades (Turfco TriWave Overseeder, Turfco Manufacturing Inc., Blaine, MN) to add incisions to the turf that were 1.9 cm deep and spaced 3.8 cm apart.

2.3.2. HTCC + VC versus VC

At the conclusion of study comparing HTCC + VC versus HTCC we decided to perform a supplementary study to evaluate HTCC + VC compared to VC. Additional verticutting and aeration with hollow tines was initiated. A summary of the management received by the plots prior to the HTCC + VC versus VC runoff event (October 9) were: HTCC on all six plots 73 days before runoff (dbr), the three plots representing HTCC + VC received VC 50 dbr and HTCC 8 dbr, and the three plots representing VC received VC 66 dbr and 8 dbr. All other experimental procedures and data collection were the same as reported for the HTCC + VC versus HTCC studies.

2.4. Pesticide application

Commercially available pesticide formulations were tank mixed and applied to all plots, at label rates perpendicular to runoff flow, using a 4.6 m spray boom fitted with TeeJet XR8004 nozzles (TeeJet Technologies) spaced 50.8 cm apart (sprayer pressure: 138 kPa, speed: 3.2 kmph). The tank mix included Dursban® 50 W insecticide (Dow AgroSciences LLC, Indianapolis, IN) containing 50% chlorpyrifos; ProStar® 70WP fungicide (Chipco® Professional Products, Aventis CropScience) containing 70% flutolanil; and Trimec® Bentgrass Formula herbicide (PBI Gordon) containing 6.12% 2,4-D, 2.53% dicamba and 9.92% mecoprop-p. Chemical names and properties of the active ingredients are provided in Table 1. Runoff collected prior to pesticide application was free of pesticide residues. No natural precipitation or irrigation occurred between completion of the pesticide application and initiation of simulated precipitation.

2.5. Simulated precipitation

All plots were saturated forty-eight hours prior to initiation of simulated precipitation, to facilitate collection of background runoff samples and ensure uniform water distribution throughout the plots. The next day flumes and runoff collection gutters were cleaned and covered with plastic sheeting to avoid contamination while applying the pesticides. The turf was mowed and Petri dishes (glass, 14-cm) were distributed across the plots to verify rates of pesticide application. Following pesticide application, Petri dishes and plastic sheeting were removed and rain gauges (12-cm, Taylor Precision Products, Las Cruces, NM) were distributed throughout each plot to quantify precipitation. Soil moisture was measured <3 h prior to initiation of simulated precipitation using a Field Scout TDR 300 (Spectrum Technologies, Plainfield, IL). Plots were hydrologically isolated with removable berms (horizontally-split 10.2-cm schedule 40 PVC pipe, inverted to rest on the cut edges) and observations confirmed no water movement between plots during runoff events. A hand-held meter (Davis Instruments, Hayward, CA, USA) was used to measure wind speeds in situ. Once wind speeds dropped below 2 ms^{-1} simulated precipitation was initiated (<24 h following pesticide application). Water was applied using a rainfall simulator, modified from the design of Coody and Lawrence (1994), to represent storm intensities recorded in Minnesota, USA,

Table 2
Soil moistures, precipitation rates and depth of precipitation measured for the runoff events.

	Soil moisture (%)[a,b]	Precipitation Rate ($mm\ h^{-1}$)[a]	Precipitation Depth (mm)[a]
HTCC + VC vs. HTCC[c]			
Runoff event-1[d]	41 ± 3	37 ± 2	75 ± 7
Runoff event-2[d]	41 ± 2	40 ± 2	73 ± 5
HTCC + VC vs. VC[c]			
Runoff event-1[d]	40 ± 6	38 ± 8	67 ± 8

[a] Data presented as the mean ± standard deviation (soil moisture n = 27, precipitation n = 36).
[b] Percentage water holding capacity 3 h prior to simulated precipitation.
[c] Hollow tine core cultivation (HTCC), Hollow tine core cultivation and verticut (HTCC + VC), verticut (VC).
[d] A runoff event represents 3 rainfall simulations. Each rainfall simulation involves a side-by-side direct comparison of the two evaluated management.

during July through October with recurrence interval of 25 years (Huff and Angel, 1992). The base of the simulator guided water to eighteen risers each equipped with a pressure regulator (Lo-Flo, 15 psi), nozzle (No. 25) and standard PC-S3000 spinner (Nelson Irrigation, Walla Walla, WA, USA) suspended 2.7 m above the turf. The rainfall simulator delivered precipitation to two plots simultaneously to allow a direct side-by-side paired comparison of the two evaluated treatments during each simulation (e.g. HTCC + VC versus HTCC, 3 paired-plot replicates per runoff event, 2 runoff events; or HTCC + VC versus VC, 3 paired-plot replicates per runoff event, 1 runoff event). A picture of the rainfall simulator is provided elsewhere (Rice and Horgan, 2017).

2.6. Pesticide analysis

Water samples (3 mL) were filtered through a 0.45 μm nylon syringe filter (Whatman) followed by a 0.5-mL methanol rinse. Each sample was analyzed for pesticides, no samples were combined. Petri dishes, containing formulated pesticide spray residues for determination of application rates, were rinsed with methanol and the rinsate was filtered (0.45 μm nylon filter) and diluted with laboratory-grade organic-free water to mimic the filtered runoff samples (14% methanol content). These measured application rates were used to calculate the percentage of applied pesticide transported with the runoff. Background runoff fortified with the target analytes, background runoff and irrigation source water served as positive control field samples and field blanks. Ten runoff samples, field blanks, field controls or application rate samples were processed in each filtration batch with an untreated laboratory-grade organic-free water sample and a laboratory-grade organic-free water sample fortified with the target analytes at the beginning and end of each batch. Pesticide concentrations were measured by direct injection (500 μL) onto a high performance liquid chromatograph (Waters model 717plus autosampler and model 1525 binary pump) with a photodiode array detector (Waters model 2996: Waters Corp., Milford, MA) set at 230 nm. Analytes were eluted from an Agilent C-18 column (150 mm long, 4.6 mm diameter, 5 μm packing) at a rate of 1 mL/min using two solvents [solvent A: laboratory-grade organic-free water (0.17% trifluoroacetic acid); solvent B: 82:18 methanol:acetonitrile]. Initial conditions, 60% B, were held for 2 min followed by a gradient ramped from 60 to 95% B in 23 min, a 3 min hold, then back to 60% B in 10 min with a 5 min hold. Chlorpyrifos, flutolanil, 2,4-D, dicamba and MCPP were identified and quantified by direct comparison with an external standard calibration curves of analytical standards. Individual stock solutions (500 ppm) of each compound of interest were prepared by dissolving the analytical standard into 10 mL of optima-grade methanol. Known quantities of each compound's stock solution were combined and diluted to create analytical standards of the pesticide mixture (6:1 water:methanol), representing 5 point standard curves that bracket expected concentrations in the runoff water samples. Average linearity, repeatability and reproducibility for the five pesticides was $r^2 = 0.99 \pm 0.01$, RSD = 8.1 ± 2.4%, RSD = 6.4 ± 2.3%, respectively. Limits of quantification were: chlorpyrifos 5.3 ± 0.9 μg/L, flutolanil 4.5 ± 0.8 μg/L, 2,4-D 4.5 ± 0.8 μg/L, dicamba 5.1 ± 0.6 μg/L and MCPP 5.3 ± 0.9 μg/L. Recoveries were: chlorpyrifos 74 ± 23%, flutolanil 91 ± 8%, 2,4-D 105 ± 11%, dicamba 102 ± 6% and MCPP 104 ± 7%.

2.7. Statistical analysis

Management practices were assigned to the plots using a randomized complete block design, which provided three replicate side-by-side comparisons of the two evaluated management practices for each runoff event. Analyses of variance were carried out to evaluate runoff volumes and pesticide loads, with management practices as the single criteria of classification for the data. Least significant difference (LSD, 0.05 = error degrees of freedom and 0.05 probability to determine two-tailed t values) established statistical significance between treatment means (Steel et al., 1997).

3. Results and discussion

3.1. HTCC + VC versus HTCC: precipitation depth and runoff volume

Simulated rainfall (duration: 1.9 ± 0.1 h) was initiated 15.3 ± 2.7 h (event-1) and 13.7 ± 3.6 h (event-2) following application of the tank-mixed pesticides. Soil moisture, precipitation rate and depth of precipitation are presented in Table 2. Resulting hydrographs and cumulative runoff volumes are provided in Fig. 1A and B, which represent an average of the hydrographs and cumulative runoff volumes measured during the simulations performed for each runoff event. Analysis of data along the hydrographs revealed greater runoff from HTCC + VC than HTCC for 68 ± 22% (53 ± 22% significant $p = 0.05$) of the data points. Cumulative runoff volumes measured from plots receiving HTCC + VC (4270 ± 453 L or 28.7 ± 3.0 mm (event-1); 4352 ± 248 L or 29.3 ± 1.6 mm (event-2)) were 10% and 11% more than plots managed with HTCC (3842 ± 183 L or 25.8 ± 1.2 mm (event-1); 3887 ± 958 L or 26.2 ± 6.4 mm (event-2)). However, this difference in cumulative runoff volumes was not statistically significant. We observed 36 ± 1.7% and 38 ± 0.4% of the applied precipitation resulted in runoff from HTCC and HTCC + VC, respectively. This was in close agreement with Shuman (2002) where runoff was 37 to 44% of simulated rainfall applied to Tifway bermudagrass (*Cynodon dactylon* L.) Pers. Soil moisture conditions between these studies were similar with simulated rainfall applied 2 days after saturation to field capacity. Core cultivation, however, was not reported. Kauffman and Watschke (2007) observed three to 21% of applied simulated precipitation was measured as runoff from bentgrass and perennial ryegrass turf managed with HTCC. They noted dissimilarity in runoff volumes were attributed to variations in antecedent soil moisture, slope and environmental conditions.

3.2. HTCC + VC versus HTCC: mass of pesticides transport with runoff

The off-site transport of pesticides with runoff from plots managed with hollow tine core cultivation, with or without verticutting, was compared using edge-of-plot pesticide loads (μg m^{-2}) calculated from measured pesticide concentrations (μg L^{-1}) in the runoff and runoff volumes (L) from the plot area (m^2). Pesticide residues were not measured in water used for the simulated rainfall treatments and turf maintenance. Flutolanil, 2,4-D, dicamba and MCPP were detected in the initial runoff sample and throughout the runoff event. Chlorpyrifos was absent in some of the initial runoff samples. The average, median, minimum and maximum concentrations (μg L^{-1}) measured in the edge-of-turf runoff are provided in Table 3. Average loads (μm^{-2}) of the paired replicates for each runoff event are presented as chemographs and cumulative loads of the applied pesticides in Fig. 2A–J. Evaluation of paired data points along the chemographs showed plots managed with HTCC + VC had greater loads then plots managed with HTCC (average ± standard deviation of runoff events 1 and 2): 76 ± 1% (66 ± 5% significant at 5%) of the flutolanil samples (Fig. 2C and D), 80 ± 6% (67 ± 16% significant at 5%) of the 2,4-D samples (Fig. 2E and F), 79 ± 17% (69 ± 18% significant at 5%) of the dicamba samples (Fig. 2G and H), and 80 ± 17% (72 ± 16% significant at 5%) of the MCPP samples (Fig. 2I and J). For chlorpyrifos (Fig. 2A and B), plots managed with HTCC + VC had greater loads then plots managed with HTCC for the second runoff event (99% (55% significant at 5%)); however, the reverse was observed during the first runoff event (HTCC > HTCC + VC: 91% (58% significant at 5%)).

Overall the total mass (cumulative load) of pesticides transported with runoff from plots managed with HTCC + VC exceeded that of plots managed with HTCC (Fig. 2B–J). For the first runoff event plots receiving HTCC + VC contained 8%, 22%, 18% and 27% greater loads of flutolanil, 2,4-D, dicamba and MCPP than plots managed with HTCC. Similarly for the second runoff event plots managed with HTCC + VC contained 24%,

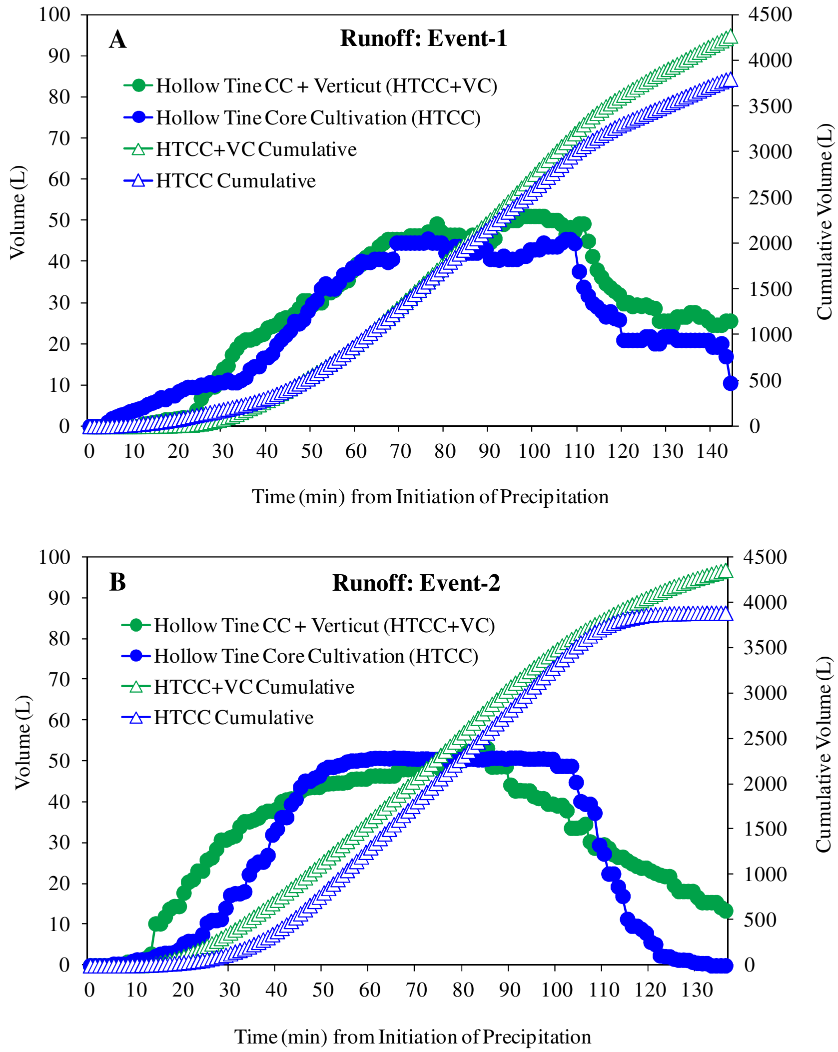


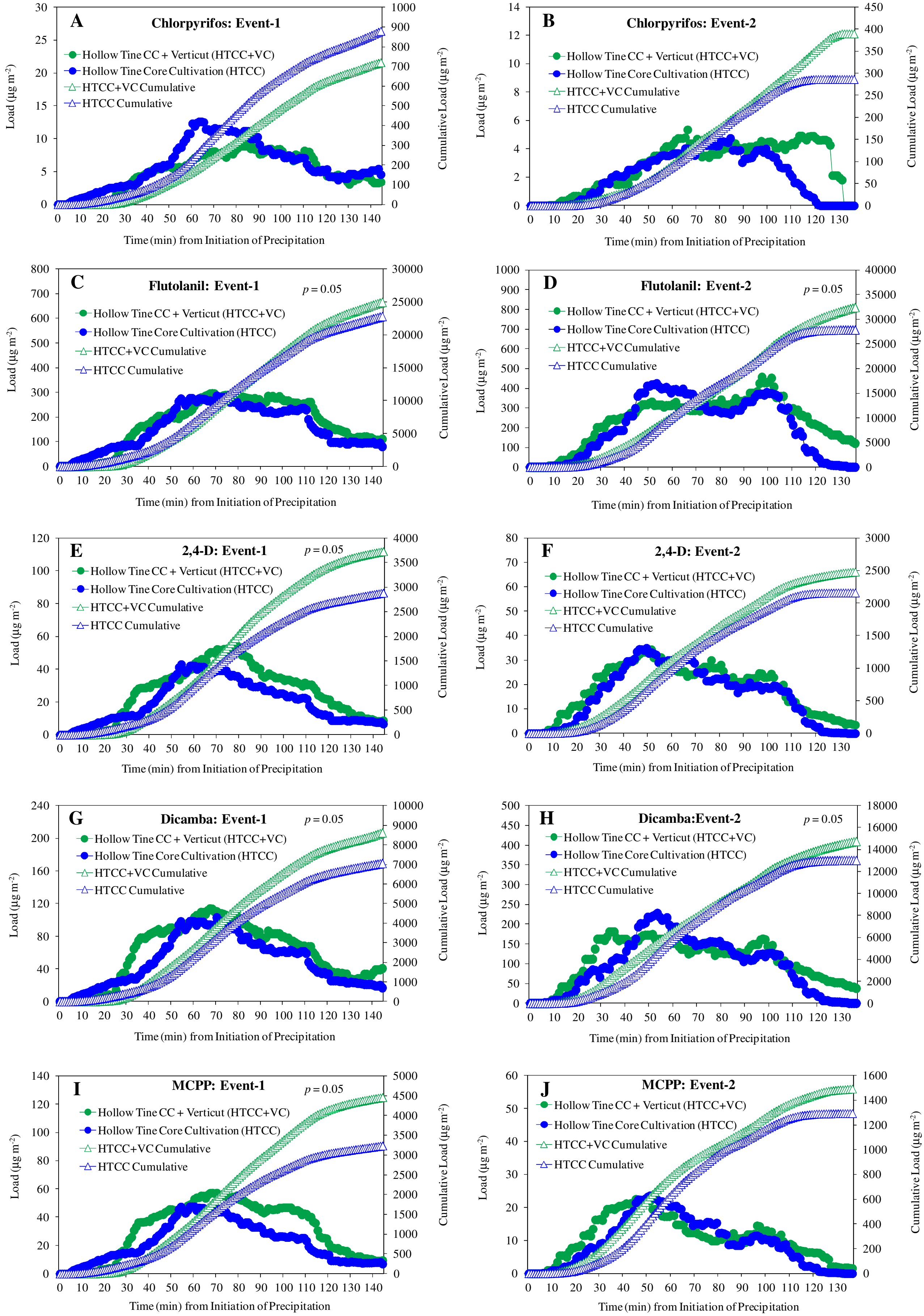
Fig. 1. Runoff hydrographs and cumulative volumes from turf plots managed with hollow tine core cultivation (HTCC) versus hollow tine core cultivation and verticutting (HTCC + VC). The presented data represents an average of the hydrographs and cumulative runoff volumes measured during the rainfall simulations performed for each runoff event.

Table 3
Concentration of pesticides measured in the edge-of-turf runoff.

	Runoff concentration (μg L^{-2})[b]					
	HTCC + VC[a]			HTCC[a]		
Pesticide	Average	Median	(Minimum–maximum)	Average	Median	(Minimum–maximum)
Chlorpyrifos[c]	18	20	(2–43)	21	19	(2–78)
Flutolanil[d]	1050	905	(24–7625)	909	950	(29–1423)
2,4-D[e]	107	93	(23–292)	95	90	(34–233)
Dicamba[f]	391	350	(22–1679)	394	363	(144–1443)
MCPP[g]	105	86	(12–347)	86	71	(12–238)

[a] Management Practices: Hollow tine core cultivation and verticut (HTCC + VC), Hollow tine core cultivation (HTCC).
[b] Combined data from runoff events 1 and 2 (n > 640).
[c] Chlorpyrifos (*O,O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate).
[d] Flutolanil (*N*-[3-(1-methylethoxy) phenyl]-2-(trifluoromethyl) benzamide).
[e] 2,4-D (dimethylamine salt of 2,4-dichlorophenoxyacetic acid).
[f] Dicamba (dimethylamine salt of 3,6-dichloro-*o*-anisic acid).
[g] Mecoprop-P (dimethylamine salt of (+)-(*R*)-2-(2-methyl-4-chlorophenoxy) propionic acid).

Fig. 2. Pesticide chemographs and cumulative pesticide loads for chlorpyrifos (A and B), flutolanil (C and D), 2,4-dichlorophenoxyacetic acid (2,4-D) (E and F), dicamba (G and H) and mecoprop-p (MCPP) (I and J) in runoff from turf plots managed with hollow tine core cultivation and verticutting (HTCC + VC) versus hollow tine tine core cultivation (HTCC). The presented data represents an average of the chemographs and cumulative loads measured during the rainfall simulations performed for each runoff event. Cumulative loads with a statistically significant difference between HTCC + VC and HTCC are marked with $p = 0.05$ in the top right corner of each graph, above the lines representing cumulative loads.


A
Chlorpyrifos: Event-1
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
B
Chlorpyrifos: Event-2
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
C
Flutolanil: Event-1
p = 0.05
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
D
Flutolanil: Event-2
p = 0.05
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
E
2,4-D: Event-1
p = 0.05
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
F
2,4-D: Event-2
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
G
Dicamba: Event-1
p = 0.05
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
H
Dicamba:Event-2
p = 0.05
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
I
MCPP: Event-1
p = 0.05
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation
J
MCPP: Event-2
Hollow Tine CC + Verticut (HTCC+VC)
Hollow Tine Core Cultivation (HTCC)
HTCC+VC Cumulative
HTCC Cumulative
Load (μg m-2)
Cumulative Load (μg m-2)
Time (min) from Initiation of Precipitation

34%, 15%, 12% and 16% greater loads of chlorpyrifos, flutolanil, 2,4-D, dicamba and MCPP than plots managed with HTCC. An exception to the observed trend was noted for chlorpyrifos in the first runoff event, which represented a 19% greater cumulative load from HTCC. Statistical analysis of cumulative pesticide loads for HTCC + VC compared to HTCC showed significance at 5% for flutolanil, 2,4-D, dicamba, and MCPP. The alternating trend and difference in cumulative chlorpyrifos loads for the two runoff events was not statistically significant.

3.3. HTCC + VC versus HTCC or VC: percentage of applied pesticides transported with runoff

Current and prior experiments were performed on the same plots using identical chemical application, rainfall simulation, and runoff collection, processing and analysis protocols. Converting data to the percentage of applied precipitation as runoff or percentage of applied pesticides transported with runoff allowed comparison of separate studies performed over a range of years.

In prior research we compared the individual management practices (VC versus HTCC) for their capacity to minimize runoff volumes and the off-site transport of pesticides with runoff from turf managed as a golf course fairway. Our results showed reduced runoff volume and quantity of herbicides (dicamba, MCPP and 2,4-D) transported with runoff from turf managed with HTCC compared to VC (Rice et al., 2011) (Fig. 3). We theorized the coupling of HTCC with VC would further enhance infiltration of precipitation and lessen runoff volumes relative to the individual management practices. Consequently we also anticipated to find reduced off-site transport of pesticides with the combined management practice. Results of the present study comparing HTCC + VC with HTCC (Fig. 4A & B) and a supplementary study comparing HTCC + VC with VC (Fig. 4C) demonstrated this was not correct. In fact, similar or greater percentages of the applied precipitation and pesticides were observed in the runoff of the combined management practices (HTCC + VC).

Quantities of pesticides detected in the runoff from turf managed with HTCC + VC, HTCC or VC (Fig. 4A–C) represent <8% of the applied insecticide or fungicide (chlorpyrifos: less than one to 2%, flutolanil: 4 to 7%) and 9 to 38% of the applied herbicides (MCPP: 9 to 30%, 2,4-D: 20 to 38%, dicamba: 30 to 37%), which is explained by the greater water solubility and lesser soil organic carbon partition coefficient (K_{OC}) of the herbicides (Table 1). Based on the applied pesticide's K_{OC} (Table 1) and the six soil mobility classes reported by Swann et al. (1983), chlorpyrifos is considered to be immobile ($K_{OC} > 5000$) while flutolanil has low mobility ($K_{OC} = 500–2000$) and MCPP, 2,4-D, and dicamba are considered to be highly mobile ($K_{OC} < 150$). It is interesting to note that although the cumulative runoff volumes observed between the management practices (HTCC + VC versus HTCC or VC) were not statistically different, the mass of pesticides transported off-site with runoff was significantly ($p = 0.05$) greater from HTCC + VC for the more mobile herbicides (dicamba, 2,4-D, MCPP). We believe this is due to the influence of each management practice. Turf management with HTCC removes cores and returns the soil back to the turf, which would increase accessibility of soil adsorptive sites and influence pesticide availability for transport (Liu et al., 1995; Gardner et al., 2000; Raturi et al., 2005). Verticutting displaces soil with blades resulting in localized compaction. Although HTCC produces compaction along the base and sidewalls of the core channel, sidewall compaction has been shown to diminished (Petrovic, 1979) and HTCC has displayed enhance water infiltration compared to untreated turf (Baldwin et al., 2006; McCarty et al., 2007). In previous work we compared runoff from turf managed with HTCC or solid tine core cultivation (STCC) using tines of the same diameter and length. Similar to VC, the solid tines did not remove soil but rather pushed soil aside to create channels. This resulted in greater localized compaction, runoff volume and pesticide transport with runoff (Rice et al., 2010a, 2010b). Others have reported the greatest localized compaction occurs at the base of the zone of cultivation for STCC (Baldwin et al., 2006; Murphy et al., 1992) and greater saturated water conductivity and air porosity has been reported in turf managed with HTCC compared to STCC (Murphy et al., 1992). We deduce that soil compaction resulting from STCC or VC is greater than HTCC as the difference we observed in percentage of applied precipitation measured as runoff from turf managed with STCC or VC was 34% and 6% greater than with HTCC, respectively. It is likely the addition of VC following HTCC further increased compaction and reduced availability of recently exposed soil adsorptive sites produced from the HTCC performed 7 days prior to the VC.

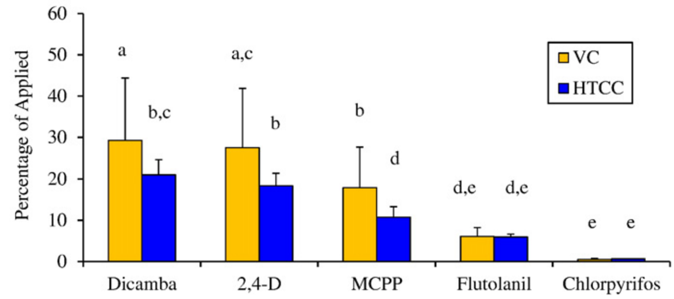


Fig. 3. Side-by-side comparison of management practices. Percentage of applied dicamba, 2,4-dichlorophenoxyacetic acid (2,4-D), mecoprop-p (MCPP), flutolanil and chlorpyrifos measured in runoff from turf plots managed with hollow tine core cultivation (HTCC) versus verticutting (VC). Standard deviations of the replicate means are presented as error bars. Means that do not share the same lowercase letter are statistically different ($p = 0.05$).

Chemical degradation was not influential in the percentage of applied pesticide in the runoff given that the time from chemical application to runoff (runoff event-1: 15.3 ± 2.7 h, runoff event-2: 13.7 ± 3.6 h) was much less than the reported half lives of the compounds of interest (120 to 7680 h; 5 to 320 d) (Table 1). The percentage of applied chlorpyrifos and flutolanil that we observed in the runoff are in range with the observations of Armbrust and Peeler (2002) and Wauchope et al. (1990) who reported <3% of imidacloprid, 2,4-D, cyanazine, and sulfometuronmethyl measured in runoff from managed turf. In the studies of Cole et al. (1997) and Ma et al. (1999) <15% of applied MCPP, dicamba and 2,4-D were measured in runoff from bermudagrass plots managed as a fairway, which is half the quantity of the maximum percentages we detected for the same herbicides. The larger percentages of applied herbicides measured with runoff in our studies comparing HTCC + VC with HTCC or HTCC + VC with VC are most likely related to the greater soil moisture. Enhanced transport of MCPP, dicamba and 2,4-D with runoff from turf has been noted during times of greater soil moistures compared to drier conditions (Cole et al., 1997).

Overall, considering trends observed in this research (HTCC versus HTCC + VC and VC versus HTCC + VC) and our prior research discussed (HTCC versus VC) we can conclude HTCC < VC < HTCC + VC for the off-site transport of the highly mobile pesticides evaluated (water solubility ≥ 860 mg L^{-1}, K_{OC} ≤ 56 mL g^{-1}; Table 1) while HTCC = VC = HTCC + VC for the pesticides evaluated with low mobility (water solubility ≤8.01 mg L^{-1}, K_{OC} ≥ 735 mL g^{-1}; Table 1). Data from the present study contribute to the understanding of pesticide transport with runoff from managed turf. Evaluation of management practices is important in order to understand their efficacy and potential contribution toward improving the environmental stewardship of managed biological systems. As benefits and improvements in management strategies are discovered they can be implemented; while practices with unexpected adverse consequences can be modified or replaced.

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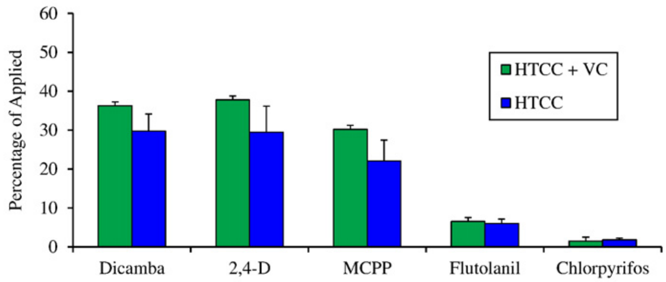

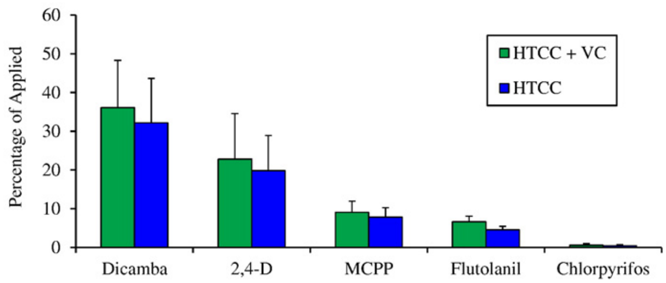

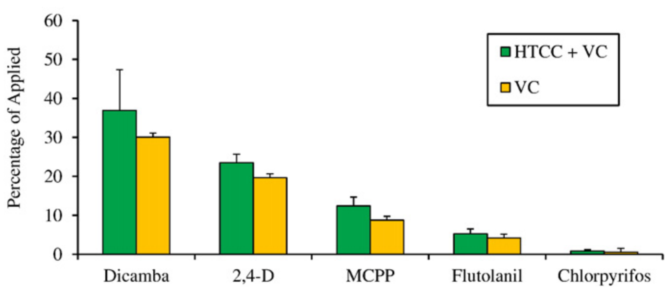

Fig. 4. Side-by-side comparison of management practices. Percentage of applied dicamba, 2,4-dichlorophenoxyacetic acid (2,4-D), mecoprop-p (MCPP), flutolanil and chlorpyrifos measured in runoff from turf plots managed with hollow tine core cultivation and verticutting (HTCC + VC) versus hollow tine core cultivation (HTCC) (A and B) and hollow tine core cultivation and verticutting (HTCC + VC) versus verticutting (VC) (C). Standard deviations of the replicate means are presented as error bars. Means that do not share the same lowercase letter are statistically different ($p = 0.05$) within each runoff event (e.g. HTCC + VC versus HTCC (A), HTCC + VC versus HTCC (B), or HTCC + VC versus VC (C)) or across runoff events (A–C).

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References

Armbrust, K.L., Peeler, H.B., 2002. Effects of formulation on the run-off of imidacloprid from turf. Pest Manag. Sci. 58, 702–706.

Bakri, D.A., Rahman, S., Bowling, L., 2008. Sources and management of urban stormwater pollution in rural catchments, Australia. J. Hydrol. 356, 299–311.

Baldwin, C.M., Liu, H., Brown, P.J., 2006. Effects of core cultivation tine entry angle on golf putting greens. Hort Technol. 16, 265–269.

Barbash, J.E., Resek, E.A., 1996. Pesticides in Groundwater: Distribution, Trends, and Governing Factors. Lewis, Boca Raton, FL.

Barton, L., Wan, G.C.Y., Buck, R.P., Colmer, T.D., 2009. Effectiveness of cultural thatch-mat controls for young and mature Kikuyu turfgrass. Agron. J. 101, 67–74.

Beard, J.B., 1973. Turfgrass: Science and Culture. Prentice-Hall, Engelwood Cliffs, NJ.

Callahan, L.L., Sanders, W.L., Parham, J.M., Harper, C.A., Lester, L.D., McDonald, E.R., 1998. Cultural and chemical controls of thatch and their influence on rootzone nutrients in a bentgrass green. Crop Sci. 38, 181–187.

Carrow, R.N., Johnson, B.J., Burns, R.E., 1987. Thatch and quality of Tifway bermudagrass turf in relation to fertility and cultivation. Agron. J. 79, 524–530.

Chandler, G., Scott, G., 1991. Effects of sediment-bound endosulfan on survival, reproduction and larval settlement of meiobenthic polychaetes and copepods. Environ. Toxicol. Chem. 10, 375–382.

Clark, J., Kenna, M., 2001. Lawn and turf: management and environmental issues of turfgrass pesticides. In: Krieger, R., Krieger, W. (Eds.), Handbook of Pesticide Toxicology, second ed. Academic Press, San Diego, CA, pp. 203–241.

Clark, J., Lewis, M., Pait, A., 1993. Pesticide inputs and risks in coastal wetlands. Environ. Toxicol. Chem. 12, 2225–2233.

Cohen, S., Svrjcek, A., Durborow, T., Barnes, N.L., 1999. Water quality impacts by golf courses. J. Environ. Qual. 28, 798–809.

Cole, J.T., Baird, J.H., Basta, N.T., Huhnke, R.L., Storm, D.E., Johnson, G.V., Payton, M.E., Smolen, M.D., Martin, D.L., Cole, J.C., 1997. Influence of buffers on pesticide and nutrient runoff from bermudagrass turf. J. Environ. Qual. 26, 1589–1598.

Coody PN, Lawrence LJ. Method and system for conducting meso-scale rainfall simulations and collecting runoff. U.S. Patent 5,279,151. U.S. Patent Office, Washington, DC. 1994.

Dunn, J.H., Minner, D.D., Fresenburg, B.F., Bughrara, S.S., Hohnstrater, C.H., 1995. Influence of core aerification, topdressing, and nitrogen on mat, roots and quality of 'Meyer'. Zoysiagrass. Agron J. 87, 891–894.

Evans, J.R., Edwards, D.R., Workman, S.R., Williams, R.M., 1998. Response of runoff diazinon concentration to formulation and post-application irrigation. Trans. ASAE 41, 1323–1329.

Fairbairn, D.J., Karpuzcu, E.M., Arnold, W.A., Barber, B.L., Kaufenberg, E.F., Koskinen, W.G., Novak, P.J., Rice, P.J., Swackhamer, D.L., 2016. Sources and transport of contaminants of emerging concern: a two-year study of occurrence and spatiotemporal variation in a mixed land use watershed. Total Sci. Environ. 551–2, 603–605.

Frick, E.A., Hippe, D.J., Buell, G.R., Couch, C.A., Hopkins, E.H., Wangsness, D.J., Garrett, J.W., 1998. Water Quality in the Apalachicola-Chattahoochee-Flint River Basins, Georgia, Alabama, and Florida, 1992–95. U.S. Geological Survey Circular 1164, Reston, VA.

Gardner, D.S., Branham, B.E., Lickfeldt, D.W., 2000. Effect of turfgrass on soil mobility and dissipation of cyproconazole. Crop Sci. 40, 1333–1339.

Gascon, M., Triguero-Mas, M., Martinez, D., Dadvand, P., Rojas-Rueda, D., Plasencia, A., Nieuwenhuijsen, M.J., 2016. Residential green spaces and mortality: a systematic review. Environ. Int. 86, 60–67.

Gianessi, L.P., Anderson, J.E., 1996. Pesticide use in U. S. crop production. National Data Report. National Center for Food and Agricultural Policy, Washington, DC, USA.

Gilliom, R.J., Barbash, J.E., Crawford, C.G., Hamilton, P.A., Martin, J.D., Nakagaki, N., Nowell, L.J., Scott, J.C., Stackelberg, E., Thelin, G.P., Wolock, D.M., 2006. Pesticides in the Nation's Streams and Ground Water, 1992–2001; Ci No. 1291. Revised Feb 2007; U.S. Geological Survey National Water-Quality Assessment Program, Reston, VA. http://pubs.usgs.gov/circ/2005/1291.

Goel, A., McConnell, L.L., Torrents, A., 2005. Wet deposition of current use pesticides at a rural location on the Delmarva Peninsula: impact of rainfall patterns and agricultural activity. J. Agric. Food Chem. 53, 7915–7924.

Golf Course Superintendents Association of America (GCSSA), 2012,. Golf course environmental profile. Pesticide Use Practices on U.S. Golf Courses. vol. 5 (25p).

Grube, A., Donaldson, D., Kiely, T., Wu, L., 2011. Pesticide Industry Sales and Usage, 2006 and 2007 Market Estimates; Office of Pesticide Programs. U.S. Environmental Protection Agency, Washington, DC (33p). https://www.epa.gov/sites/production/files/2015-10/documents/market_estimates2007.pdf.

Harman-Fetcho, J., Hapeman, C., McConnell, L., Potter, T., Rice, C., Sadeghi, A., Smith, R., Bialek, K., Sefton, K., Schaffer, B., 2005. Pesticide occurrence in selected South Florida canals and Biscayne Bay during high agricultural activity. J. Agric. Food Chem. 53, 6040–6048.

Harris, J.R., 1978. Maintenance of soil structure under playing turf. In: Emerson, W.W. (Ed.), Modifications of Soil Structure. John Wiley & Sons, Chichester, England.

Hayward, S., Gouin, T., Wania, F., 2010. Levels and seasonal variability of pesticides in the rural atmosphere of southern Ontario. J. Agric. Food Chem. 58, 1077–1084.

Hoffman, R.S., Capel, P.D., Larson, S.J., 2000. Comparison of pesticides in eight U.S. urban streams. Environ. Toxicol. Chem. 19, 2249–2258.

Huff, F.A., Angel, J.R., 1992. Rainfall Frequency Atlas of the Midwest, Bulletin 71, MCC Research Report 92–03. Midwest Climate Center and Illinois State Water Survey, Champaign, IL. http://www.isws.illinois.edu/pubdoc/B/ISWSB-71.pdf.

Jeffries, M.D., Gannon, T.W., Brosnan, J.T., Breeden, G.K., 2016. Mitigation practices to effectively overseed into indaziflam-treated turfgrass areas. Weed Technol. 30, 154–162.

Joyce, S., 1998. Why the grass isn't always greener. Environ. Health Perspect. 106A, 378–383.

Kauffman, G.L., Watschke, T.L., 2007. Phosphorus and sediment in runoff after core cultivation of creeping bentgrass and perennial ryegrass turfs. Agron. J. 99, 141–147.

Kitchen, K., July 8, 2014. Aeration vs. verticutting. Sports Turf Yearly Maintenance . http://cwsportsturf.com/blog/aeration-vs-verticutting/ (last accessed December 6, 2016).

Liu, L.X., Hsiang, T., Eggens, J.L., 1995. Core cultivation and efficacy of benomyl applied to creeping bentgrass. Agron. J. 87, 272–275.

Loague, K., Soutter, L., 2006. Desperately seeking a cause for hotspots in regional-scale groundwater plumes resulting from non-point source pesticide applications. Vadose Zone J. 5, 204–221.

Lv, J., Shi, R., Cai, Y., Liu, Y., Wang, Z., Feng, J., Zhao, M., 2010. Assessment of 20 organochlorine pesticides (OCPs) pollution in suburban soil in Tianjin, China. Bull. Environ. Contam. Toxicol. 85 (2), 137–141 (0007–4861).

Ma, Q.L., Smith, A.E., Hook, J.E., Smith, R.E., Bridges, D.C., 1999. Water runoff and pesticide transport from a golf course fairway: observations vs. Opus model simulations. J. Environ. Qual. 28, 1463–1473.

Manahan, S.E., 1994. Environmental Chemistry. sixth ed. Lewis, Boca Raton, FL.

Margni, M., Rossier, D., Crettaz, P., Jolliet, O., 2002. Life cycle impact assessment of pesticides on human health and ecosystems. Agric. Ecosyst. Environ. 93, 379–392.

Matsumura, F., 1985. Toxicology of Insecticides. Plenum Press, New York.

McCarty, L.B., Gregg, M.F., Toler, J.E., Camberato, J.J., Hill, H.S., 2005. Minimizing thatch and mat development in a newly seeded creeping bentgrass golf green. Crop Sci. 45, 1529–1535.

McCarty, L.B., Gregg, M.F., Toler, J.E., 2007. Thatch and mat management in an established creeping bentgrass golf green. Agron. J. 99, 1530–1537.
Mekonen, S., Argaw, R., Simanesew, A., Houbraken, M., Senaeve, D., Ambelu, A., Spanoghe, P., 2016. Pesticide residues in drinking water and associated risk to consumers in Ethiopia. Chemosphere 162, 252–260.
Miller, R.W., 1965. The thatch problem. Weeds Trees Turf 4, 10–18.
Montuori, P., Aurino, S., Garzonio, F., 2016. Polychlorinated biphenyls and organochlorine pesticides in Tiber River and estuary; occurrence, distribution and ecological risk. Sci. Total Environ. 571, 1001–1016.
Moss, J.Q., Bell, G.E., Martin, D.L., Payton, M.E., 2007. Nutrient runoff from Bermudagrass golf course fairways after aerification. J. Appl. Turfgrass Sci. http://dx.doi.org/10.1094/ATS-2007-0125-02-RS.
Murphy, J.A., Rieke, P.E., Erickson, A.E., 1992. Core cultivation of a putting green with hollow and solid tines. Agron. J. 85, 1–9.
Murray, J.J., Juska, F.V., 1977. Effects of management practices on thatch accumulation, turf quality, and leaf spot damage in common Kentucky bluegrass. Agron. J. 69, 365–369.
Nash, D., Clemow, L., Hannah, M., Barlow, K., Gangaiya, P., 2005. Modeling phosphorus exports from rain-fed and irrigated pastures in southern Australia. Aust. J. Soil Res. 43, 745–755.
Nektarios, P.A., Petrovic, A.M., Steenhuis, T.S., 2007. Preferential flow in simulated greenhouse golf putting green profiles as affected by aeration and two soil moisture regines. Soil Sci. 172, 108–123.
Petrovic, A., 1979. Dissertation abstract, ADG80-06178. Michigan State University Lansing, MI. http://guides.lib.msu.edu/page.phtml?page_id=1312.
Racke, K., 2000. Pesticides for turfgrass pest management: Uses and environmental issues. In: Clark, J., Kenna, M. (Eds.), Fate and Management of Turfgrass Chemicals. ACS Symposium Series Vol. 743. American Chemical Society, Washington, DC, pp. 45–64.
Raturi, S., Islam, K.R., Caroll, M.J., Hill, R.L., 2005. Carbaryl, 2,4-D, and triclopyr adsorption in thatch-soil ecosystems. J. Environ. Sci. Health B 40, 697–710.
Rice, P.J., Horgan, B.P., 2011. Nutrient loss with runoff from fairway turf: an evaluation of core cultivation practices and their environmental impact. Environ. Toxicol. Chem. 30, 2473–2480.
Rice, P.J., Horgan, B.P., 2013. Evaluation of nitrogen and phosphorus with runoff from fairway turf managed with hollow tine core cultivation and verticutting. Sci. Total Environ. 456–7, 61–68.
Rice, P.J., Horgan, B.P., 2017. Off-site transport of fertilizer with runoff from golf course fairway turf: a comparison of creeping bentgrass with a fine fescue mixture. Sci. Total Environ. 580, 533–539.
Rice, P.J., Horgan, B.P., Rittenhouse, J.L., 2010a. Pesticide transport with runoff from creeping bentgrass turf: relationship of pesticide properties to mass transport. Environ. Toxicol. Chem. 29, 1209–1214.
Rice, P.J., Horgan, B.P., Rittenhouse, J.L., 2010b. Evaluation of core cultivation practices to reduce ecological risk of pesticides in runoff from *Agrostis palustris*. Environ. Toxicol. Chem. 29, 1215–1223.
Rice, P.J., Horgan, B.P., Rittenhouse, J.L., 2011. Effectiveness of cultivation practices to minimize the off-site transport of pesticides in runoff from managed turf. In: Goh, K., Brain, B., Potter, T., Gan, J. (Eds.), Pesticide Mitigation Strategies for Surface Water Quality. American Chemical Society Symposium Series, Washington DC, pp. 95–113.
Riederer, A., Smith, K., Barr, D., Hayden, S., Hunter, R., Ryan, B., 2010. Current and historical used pesticides in residential soil from 11 homes in Atlanta, Georgia, USA. Arch. Environ. Contam. Toxicol. 58 (4), 908–917 (0090-4341).
Rowland, J.H., Cisar, J.L., Snyder, G.H., Sartain, J.B., Wright, A.L., 2009. USGA ultradwarf Bermudagrass putting green properties as affected by cultural practices. Agron. J. 101, 1565–1572.
Saito, O., 2010. Measuring the lifecycle carbon footprint of a golf course and greening the golf industry in Japan. Available from. http://www.thesustainabilitysociety.org.nz/conference/2010/papers/Saito.pdf.
Schulz, R., 2004. Field studies on exposure, effects, and risk mitigation of aquatic nonpoint-source insecticide pollution: a review. J. Environ. Qual. 33, 419–448.
Shuman, L.M., 2002. Phosphorus and nitrate nitrogen in runoff following fertilizer application to turfgrass. J. Environ. Qual. 31, 1710–1715.
Silva, E., Daam, M.A., Cerejeira, M.J., 2015. Aquatic risk assessment of priority and other river basin specific pesticides in surface water of Mediterranean river basins. Chemosphere 135, 394–402.
Slavens, M.R., Petrovic, A.M., 2012. Pesticide fate in sodded Kentucky bluegrass lawns in response to irrigation. Acta Agric. Scand. Sect. B Soil Plant Sci. 62 (Supplement 1), 86–95.
Smith, A.E., Bridges, D.C., 1996. Movement of certain herbicides following application to simulated golf course greens and fairways. Crop Sci. 36, 1439–1445.
Soulsby, C., Rodgers, P.J., Petry, J., Hannah, D.M., Malcolm, I.A., Dunn, S.M., 2004. Using tracers to upscale flow path understanding in mesoscale mountainous catchments: two examples from Scotland. J. Hydrol. 291, 174–196.
Starrett, S.K., Christians, N.W., Austin, T.A., 1996. Movement of pesticides under two irrigation regimes applied to turfgrass. J. Environ. Qual. 25, 566–571.
Steel, R.G.D., Torrie, J.H., Dickey, D.A., 1997. Principles and Procedures of Statistics: A Biometrical Approach. third ed. McGraw-Hill, New York, NY.
Stier, J.C., Hollman, A.B., 2003. Cultivation and topdressing requirements for thatch management in A and G bentgrass and creeping bluegrass. Hortic. Sci. 38, 1227–1231.
Swann, R.L., Laskowski, D.A., McCall, P.J., Vander Kuy, K., Dishburger, H.J., 1983. A rapid method for the estimation of the environmental parameters octanol/water partition coefficient, soil sorption constant, water to air ratio and water solubility. Residue Rev. 85, 17–28.
Torisello, J., 2007. Promote growth (Turfgrass maintenance). Golf Course Industry (August 21) Available from. http://www.golfcourseindustry.com/Article.aspx?article_id=71488.
Turgeon, A.J., 1985. Turfgrass Management. second ed. Reston Publishing, Reston, VA.
Vargas, J.M., Turgeon, A.J., 2004. *Poa annua*: Physiology, Culture, and Control of Annual Bluegrass. John Wiley & Sons, Hoboken, NJ.
Waltz, C., September 2007. BMPs for turfgrass water conservation in landscapes. University of Georgia Cooperative Extension Bulletin 1329 Available from. http://apps.caes.uga.edu/urbanag/pubs/bmp_watercon.pdf (42 pp).
Wauchope, R.D., Williams, R.G., Marti, L.R., 1990. Runoff of sulfometuron-methyl and cyanazine from small plots: effects of formulation and grass cover. J. Environ. Qual. 19, 119–125.
Weber, J., Halsall, C., Muir, D., Teixeira, C., Small, J., Solomon, K., Hermanson, M., Hyung, H., Bidleman, T., 2010. Endosulfan, a global pesticide: A review of its fate in the environment and occurrence in the Artic. Sci. Total Environ. 408 (15), 2966–2984 (0048-9697).
White, R.H., Dickens, R., 1984. Thatch accumulation in bermudagrass as influenced by cultural practices. Agron. J. 76, 19–22.
Wong, H., Haith, D.A., 2013. Volatilization of pesticides from golf courses in the United States: mass fluxes and inhalation health risks. J. Environ. Qual. 42, 1615–1622.
World Golf, 2016. Golf courses of the world. http://www.worldgolf.com/courses (last accessed September 22, 2016).
World Golf Foundation, 2016. Golf and the environment. http://www.worldgolffoundation.org/industry-initiatives/golf-the-environment (last accessed September 22, 2016).
Wotzka, P.J., Lee, J., Capel, P.D., Lin, M., 1994. Pesticide concentrations and fluxes in an urban watershed. AWRA Technical Publication Series TPS-94-4. American Water Resources Association, Herndon, VA, pp. 135–145.
Xu, L., Zhang, Q., Li, H., Viney, N.R., Xu, J., Liu, J., 2007. Modeling of surface runoff in Xitiaoxi catchment, China. Water Resour. Manag. 21, 1313–1323.