Urban Pesticides Risk Assessment and Management

EVALUATION OF CORE CULTIVATION PRACTICES TO REDUCE ECOLOGICAL RISK OF PESTICIDES IN RUNOFF FROM AGrostis PALustris

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Abstract—Pesticides associated with the turfgrass industry have been detected in storm runoff and surface waters of urban watersheds, invoking concern of their potential environmental effects and a desire to reduce their transport to nontarget locations. Quantities of chlorpyrifos, dicamba, dimethylamine salt of 2,4-dichlorophenoxyacetic acid (2,4-D), flutolanil, and meprop-prop (MCP) transported in runoff from bentgrass (Agrostis palustris) fairway turf managed with solid tine (ST) or hollow tine (HT) core cultivation were compared to determine which cultivation practice is more efficient at mitigating environmental risk. Plots receiving HT core cultivation showed a 10 and 35% reduction in runoff volume and a 15 to 57% reduction in pesticide transport with runoff at 63 d and 2 d following core cultivation. Estimated environmental concentrations of the pesticides in a surface water receiving runoff from turf managed with ST core cultivation exceeded the median lethal concentration (LC50) or median effective concentration (EC50) of nine aquatic organisms, lessening risk associated with pesticides in runoff from the fairway turf. Results of the present study provide quantitative information that will allow for informed decisions on cultural practices that can maximize pesticide retention at the site of application, improving pest control in turf while minimizing environmental contamination and adverse effects associated with the off-site transport of pesticides. Environ. Toxicol. Chem. 2010;29:1215–1223. © 2010 SETAC

Keywords—Core cultivation  Pesticides  Risk assessment  Runoff  Turf

INTRODUCTION

The detection of pesticides in surface waters has led to increased environmental concern and greater suspect of contaminant contributions from residential, urban, and recreational sources, in addition to the traditional agricultural inputs [1,2] (http://pubs.usgs.gov/circ/2005/1291). Pesticides are applied to highly managed biotic systems such as agricultural crops, golf courses, and commercial landscapes. Runoff from these managed areas may contribute to the degradation of water quality in surrounding surface waters depending on the quantity of runoff and level of contaminants. Golf course turf often requires multiple applications of pesticides at rates that exceed those typically found in agricultural or home environments [3,4]. Fairways comprise approximately one-third of a typical golf course [5], which may be adjacent to surface waters such as ponds, streams, and lakes. Pesticides associated with the turfgrass industry have been detected in surface waters of urban watersheds [2,6]. Examples include reports of 2,4-dichlorophenoxyacetic acid (2,4-D), dicamba, and meprop-prop (MCP) in 85% of evaluated storm runoff events, and spring and summer detections of carbaryl and diazinon at levels that exceeded criteria for the protection of aquatic life [1,7,8].

Golf course fairways and greens are often managed with core cultivation during the spring or fall to control thatch, alleviate surface compaction, enhance water infiltration, and stimulate root and shoot growth [9–14]. Although a limited amount of thatch is beneficial to lessen weed invasion, moderate soil temperatures, and enhance turf durability, an excessive thatch mat can reduce water infiltration and hydraulic conductivity, increase disease and pest pressure, and reduce cold temperature tolerance [11,13,15–17]. Cultivation with hollow tines (HTs) typically involves removing cores from the turf, which are air dried and brushed back into the open holes. Solid tine (ST) core cultivation requires a reduced amount of labor and is less disruptive to the surface of the turf but is believed to cause localized compaction [18].

Management practices have been shown to reduce runoff and pesticides transported with runoff from agricultural crops [19–21]. A number of studies have evaluated management and cultural practices for turfgrass and their influence on turf quality [18,22–24], runoff volume ([25,26]; http://dx.doi.org/10.1094/ATS-2007-0125-02-RS), and nutrient and pesticide transport with leachate [27–29] and runoff [25,26,30–32]. Despite the widespread use of ST and HT core cultivation, there are no reports comparing the quantity of pesticides transported in runoff from these two cultivation practices and their potential impact on the environment. The goal of the present study is to identify which cultural practice, ST or HT, maximizes pesticide retention at the site of application, thereby improving desired results of disease and pest control in turf while minimizing environmental contamination and adverse effects associated with the off-site transport of pesticides. The specific objectives of the present study were to quantify runoff volumes and mass of pesticides transported in runoff from creeping bentgrass turf managed with ST or HT core cultivation, calculate estimated environmental concentrations (EEC) anticipated to occur in a body of water receiving the runoff from turf managed with either ST or HT core cultivation, and compare EEC of pesticides in a receiving surface water with toxicological endpoints to determine which core cultivation practice will be more efficient at mitigating environmental risk.
MATERIALS AND METHODS

Site description

Experiments were conducted on 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, USA. This 976-m² site contained a natural slope running east to west that was graded to 4% with less than 1% slope from north to south. The soil was characterized as Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed superactive, mesic Typic Hapludolls) with 55% silt, 29% sand, 16% clay, and 3% organic carbon. The study area was sodded with L-93 creeping bentgrass (Agrostis palustris Huds.) and divided into plots (24.4 m × 6.1 m, length × width), prepared in an east-to-west direction, 14 months prior to initiation of the reported studies. The turf was managed as a fairway with a 1.25-cm height of cut (three times weekly, clippings removed), periodic (weekly) sand top dressing (1.6 mm), and maintained with sprinkler irrigation.

Runoff collection systems were constructed at the western end of each plot, modified from the design of Cole et al. [30]. Stainless steel flashing guided the runoff from the turf into 6.1-m gutters, constructed from two 3.0-m long horizontally split 15.2-cm schedule 40 polyvinyl chloride (PVC) pipe that were joined in the center with a PVC-T (15.2 cm × 15.2 cm × 15.2 cm). Water traveled from the runoff gutter to a large stainless steel 60 V trapezoidal flume (Plasti-Fab) equipped with a bubble tube port and two sample collection ports. Sand-filled trenches supported the runoff gutter and flume, maintaining a less than or equal to 2% slope for the gutter while providing level conditions for the flume. This environment encouraged water flow in the gutter while negating friction effects, and provided level flume conditions for accurate measurements of runoff volume and flow rate. Polyester landscape cloth covered the soil under the metal flashing to maintain soil structure while large nails held the flashing in place and paraffin wax provided a watertight seal along the turf. Gutter covers and flume shields prevented dilution of runoff with precipitation.

Management practices

Plots were aerated twice (June 21, Sept 28) with either STs (0.95-cm diameter × 11.43-cm length, plots 1, 3, and 6) or HTs (0.95-cm internal diameter × 11.43-cm length, plots 2, 4, and 5) and top dressed weekly with sand. Cores removed with the hollow tines were allowed to dry, broken into smaller pieces, and worked back into the turf. A leaf rake and backpack blower removed the turf and thatch from the plot surface. Sand top dressing was not performed immediately after core cultivation or within a week of simulated precipitation and generation of runoff.

Pesticides

The following pesticides were monitored in the present study: Durban® 50W insecticide (Dow AgroSciences) containing 50% chlorpyrifos (O,O-diethyl O-(3,5,6-trichloro-2-pyridinyl) phosphorothioate); ProStar® 70WP fungicide (Chipco® Professional Products, Aventis CropScience) containing 70% flutolanil (N-(3-1-methylethoxy) phenyl-2-(trifluoromethyl) benzamide); and Trimec® 2,4-D ester (Bentgrass Formula herbicide (PBI Gordon) containing 9.92% Mecoprop-p (dimethylamine salt of 3-[+]-[R]-2-[2-methyl-4-chlorophenoxo] propionic acid), 6.12% 2,4-D (dimethylamine salt of 2,4-dichlorophenoxyacetic acid), and 2,53% dicamba (dimethylamine salt of 3,6-dichloro-α-anisic acid). These commercially available products were tank mixed and applied at label rates to all plots perpendicular to runoff flow, at a speed of 3.2 km/h from a 4.6-m spray boom fitted with TeeJet XR8004 nozzles (TeeJet Technologies) spaced 50.8 cm apart with a sprayer pressure of 138 kPa. Properties of the active ingredient are provided in Table 1.

Simulated precipitation

A rainfall simulator was constructed to deliver precipitation to two 24.4-m × 6.1-m plots simultaneously (plots 1 and 2, plots 3 and 4, or plots 5 and 6). The design followed that of U.S. patent 5,279,151 [33], which delivers precipitation with a droplet size spectrum, impact velocity, spatial uniformity, and intensity similar to natural precipitation. Basically, 5-cm schedule 40 PVC pipe functioned as the base of the simulator, which guided water to 18 2.54-cm schedule 40 PVC risers, each fitted with a pressure regulator (Lo-Flo, 15 psi) and a nozzle (No. 25) containing a standard PC-S3000 spinner (Nelson Irrigation). Risers were spaced 3.7 m apart with nozzles and spinners suspended 2.7 m above the turf. Measured rainfall rates were 29 ± 5 mm/h, similar to storm intensities recorded in Minnesota, USA, during July through October. The duration of the simulated precipitation was 2.0 ± 0.5 h, which was chosen to assure 90 min of runoff had been generated from each plot. The average precipitation rate and duration of the simulated rainfall events represent a 2-h storm with recurrence interval of 25 years (Rainfall Frequency Atlas of the Midwest, Bulletin 71, Illinois State Water Survey, Champaign, IL, USA).

Prior to initiation of simulated precipitation (48 h), each plot was prewet with the maintenance irrigation beyond soil saturation to allow for collection of background samples and to ensure uniform water distribution. 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 pesticide application. Prior to chemical application, Petri dishes (glass, 14-cm) were distributed across the plots to verify pesticide delivery and application rates. Plastic sheeting and Petri dishes were removed following chemical application and 12-cm rain gauges (Taylor Precision Products) were distributed throughout each plot to quantify simulated precipitation. Plots were hydrologically isolated with removable berms, constructed from horizontally split 10.2-cm schedule 40 PVC pipe, inverted to rest on the cut edges. Wind speeds were monitored with a hand-held meter (Davis Instruments). When wind speeds dropped and remained below 2.2 m/s rainfall simulations were initiated and continued until runoff had been generated for a minimum of 90 min. Overall, simulated precipitation was initiated 26 ± 13 h after pesticide application when the wind speeds averaged 0.8 ± 0.7 mps (1.8 ± 1.6 mph).

Table 1. Pesticide properties

<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Water solubility (20°C)</th>
<th>Soil Water-sediment</th>
<th>Water</th>
<th>Half life (d)</th>
</tr>
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<tr>
<td>Chlorpyrifos</td>
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<td>50</td>
<td>37</td>
<td>5</td>
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<tr>
<td>Dicamba</td>
<td>250,000 mg/kg</td>
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<td>41</td>
<td>40</td>
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<tr>
<td>Flutolanil</td>
<td>8.01 mg/L</td>
<td>233</td>
<td>320</td>
<td>37</td>
</tr>
<tr>
<td>MCPA</td>
<td>860 mg/kg</td>
<td>8</td>
<td>50</td>
<td>37</td>
</tr>
<tr>
<td>2,4-D</td>
<td>23,180 mg/kg</td>
<td>10</td>
<td>29</td>
<td>29</td>
</tr>
</tbody>
</table>

b: Mecoprop-p-p.  
c: 2,4-dichlorophenoxyacetic acid.
Sample collection

Within 3 h prior to initiation of simulated precipitation soil moisture was measured with a soil moisture meter (Field Scout TDR 300, Spectrum Technologies). Runoff water samples were collected in glass bottles (350 ml) using an automated sampler (Teledyne ISCO model 6700) equipped with a flow meter (Teledyne ISCO model 730) that recorded water level in the flume, calculated flow rates, reported total runoff volume, and collected 24 time-paced (5 min) samples from each plot. Irrigation source water, background runoff, background runoff fortified with the target analytes, and runoff water samples were stored at −20°C until laboratory analysis.

Pesticide analysis

Runoff samples (3 ml) were filtered through a 0.45-μm nylon syringe filter (Whatman) followed by methanol (0.5 ml) to rinse the filter. Petri dishes, containing pesticide residues for determination of actual application rates, were rinsed with methanol and the filtered rinsate (0.45-μm nylon filter) was diluted with laboratory-grade organic-free water to 14% methanol to mimic the methanol and water content of the filtered runoff samples. Runoff and application rate samples were processed in groups of 10 with an untreated laboratory-grade organic-free water sample fortified with the target analytes at the beginning and end of each filtration batch. Concentrations of chlorpyrifos, dicamba, flutolanil, MCPP, and 2,4-D were measured by direct injection of 500 μl of the filtered sample onto a high-performance liquid chromatograph (Waters model 717plus autosampler and model 1525 binary pump) with a photodiode array detector (Waters model 2996) set at 230 nm. 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 (Agi lent) at a rate of 1 ml/min. 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. Analytes were identified and quantified by direct comparison with seven-point external standard calibration curves of the analytical standards. Method detection limits ranged from 2.5 to 3.7 μg/L. Limits of quantification were as follows: chlorpyrifos 5.3 ± 0.9 μg/L, dicamba 5.1 ± 0.6 μg/L, flutolanil 4.5 ± 0.8 μg/L, MCPP 5.3 ± 0.9 μg/L, and 2,4-D 4.5 ± 0.8 μg/L. Recoveries were: chlorpyrifos 74 ± 23%, dicamba 102 ± 6%, flutolanil 91 ± 8%, MCPP 104 ± 7%, and 2,4-D 105 ± 11%. Chromatograms of the analytical standards in laboratory-grade organic-free water, a filtered rinsate (0.45-μm), were processed in groups of 10 with an untreated laboratory-grade organic-free water sample fortiﬁed with the target analytes. Runoff and application rate samples were processed in groups of 10 with an untreated laboratory-grade organic-free water sample fortiﬁed with the target analytes.

Calculation of pesticide loads

Pesticide loads (\(P_L\), μg/m²) from edge-of-plot runoff were calculated by

\[
P_L = \frac{\sum (P_C \cdot R_F \cdot T_M)}{F_A}
\]

where \(P_C\) is the measured pesticide concentration (μg/L) in the runoff sample (n = 24 per plot per runoff event), \(R_F\) is the runoff flow rate (L/min) at the time of sampling, \(T_M\) denotes the time (min) between samples, and \(F_A\) is the area (m²) of the fairway turf plots. Estimated environmental concentrations (EEC) of pesticides in a surface water receiving runoff from fairway turf were calculated based on subwatershed characteristics and receiving surface water dimensions reported from a golf course located less than 20 miles from the present study site (http://www.pca.state.mn.us/publications/stormwaterresearch-eagelake.pdf, pond 4 subwatershed). Using this scenario, pesticide loads in edge-of-turf runoff \((P_L, \mu g/m^2)\) were extrapolated to pesticide concentrations in a receiving surface-water \((C_S, \mu g/L)\) by

\[
C_S = \frac{(P_L \cdot (A_G \cdot F_G))}{S_Y}
\]

where \(A_G\) (5,641 m²) is the area of the golf course contributing runoff to the receiving surface water, \(F_G\) (0.33 or 33%) is the estimated percentage of the golf course represented by fairway turf [5], and \(S_Y\) (440,000 L) is the volume of the receiving surface water. Estimated pesticide concentrations of the surface water receiving runoff from fairway turf managed with ST or HT core cultivation were compared to toxicological endpoints to evaluate which core cultivation practice would be the most efficient at mitigating environmental risk.

Statistical analysis

A randomized complete block design was used to assign each core cultivation treatment, ST or HT, to three plots. Each
RESULTS AND DISCUSSION

Simulated precipitation

Precipitation and resulting runoff were initiated on August 23, 2005 and September 30, 2005 while the turf was actively growing (mean air temperatures: August 1–31 (71 °F), September 1–30 (67 °F)). The rainfall simulator delivered 59 ± 5 mm of precipitation at a rate of 34 ± 3 mm/h (n = 36) for the first precipitation event, and 45 ± 8 mm precipitation at a rate of 24 ± 4 mm/h (n = 36) for the second precipitation event. Variations in generated rainfall rates for the two simulation events were most likely the result of changes in pressure at the water source. Measured coefficient of uniformity for the rainfall simulator was 82 to 84%. Soil moistures were 46 ± 7% water holding capacity within 3 h prior to initiation of the simulated precipitation and 67 ± 6% water holding capacity less than 2 h following simulated precipitation.

Runoff volume

The period of time between core cultivation and simulated precipitation was greater for the first runoff event (63 d) than the second runoff event (2 d) due to a delay in the construction of the rainfall simulator. The time between pesticide application and runoff were 26 ± 13 h for both runoff events. Differences were noted in the results of the 63 d and 2 d data; however, the overall trends observed between ST and HT core cultivation remained the same and supported each other.

Overall, runoff was reduced in fairway turf plots aerated with HT compared to ST core cultivation. Evaluation of hydrographs representing mean runoff volumes revealed reduced runoff volumes with HT for more than 80% of the samples (63 d = 81%, 2 d = 87%) (Fig. 2A and B). Calculation of cumulative runoff volumes from plots receiving core cultivation 63 d prior to rainfall simulation demonstrated a 10% reduction in cumulative runoff volume with HT relative to ST (HT = 3,149 ± 932 L; ST = 3,490 ± 1,107 L) (Fig. 2A). Similar trends were observed when plots were aerated 2 d prior to simulated rainfall and runoff. However, a greater difference between management practices was observed resulting in a 55% reduction in cumulative runoff volume from HT plots (HT = 1,856 ± 139 L; ST = 4,164 ± 1,698 L) (Fig. 2B). The percentage of precipitation resulting as runoff from plots aerated with HT was less than quantities observed from the ST plots, suggesting greater infiltration with HT core cultivation (63 d, HT = 36 ± 11%, ST = 41 ± 13%; 2 d, HT = 28 ± 2%, ST = 62 ± 25%). Other researchers have measured enhanced water infiltration in turf managed with HT core cultivation compared to untreated turf [22,23] and greater saturated water conductivity and air porosity in turf managed with HT compared to ST [18]. Cultivation with ST has the potential to cause localized compaction with the most severe compaction at the bottom of the zone of cultivation [18]. Likewise, HT core cultivation has been shown to result in compaction along the sidewalls and the bottom of the core where compaction remaining after 95 d while sidewall compaction had dissipated (A.M. Petrovic, 1979, Dissertation Abstract ADG80-06178, Michigan State University; http://guides.lib.msu.edu/page.xhtml?page_id = 1312). The greatest difference in soil physical properties between plots managed with ST or HT is most prominent shortly after cultivation and diminishes with time as roots grow, compaction dissipates, and holes are covered or filled, resulting in the greater distinction in runoff volumes between treatments at 2 d following cultivation compared to 63 d. The percentage of applied water as runoff measured at 63 d following core cultivation were similar to the findings of Shuman [35] were 37 to 44% of applied water resulted as runoff from fairways of Tifway bermudagrass (Cynodon dactylon [L.] Pers.), which received 50 mm of simulated precipitation 2 d following irrigation to field capacity. Kaufman and Watschke [25] report 3 to 21% of applied simulated precipitation was measured as runoff from bentgrass and perennial ryegrass turf managed with HT core cultivation. They observed that variations in runoff volumes were attributed to differences in antecedent soil moisture, slope, and environmental conditions.

Chemical transport with runoff

The off-site transport of applied chemicals was evaluated by comparing measured pesticide concentrations (µg/L) in edge-of-plot runoff and calculating chemical loads (µg/m²). All chemicals of interest were detected in the initial runoff sample...
and throughout the runoff event, with the exception of chlorpyrifos. Greater concentrations of pesticides were measured in runoff from the ST plots compared to the HT plots at 63 d following core cultivation (chlorpyrifos: ST = 4 to 22 μg/L, HT = 0 to 20 μg/L; dicamba: ST = 135 to 287 μg/L, HT = 115 to 255 μg/L; flutolanil: ST = 1,113 to 1,407 μg/L, HT = 664 to 1,306 μg/L; MCPP: ST = 120 to 298 μg/L, HT = 76 to 264 μg/L; 2,4-D: ST = 53 to 135 μg/L, HT = 32 to 137 μg/L). The reverse was observed for runoff collected 2 d following core cultivation (chlorpyrifos: ST = 4 to 60 μg/L, HT = 7 to 53 μg/L; dicamba: ST = 151 to 255 μg/L, HT = 210 to 321 μg/L; flutolanil: ST = 432 to 1,190 μg/L, HT = 973 to 1,548 μg/L; MCPP: ST = 123 to 446 μg/L, HT = 169 to 498 μg/L; 2,4-D: ST = 65 to 173 μg/L, HT = 91 to 231 μg/L).

When runoff volumes were considered and chemical loads calculated, the overall mass of pesticides transported with runoff from ST plots exceeded that of HT plots regardless of the trends observed with the concentrations. Plots receiving HT core cultivation had reduced percentage of applied active ingredient in the runoff (r² = 0.79, concentration r² = 0.17; ST 63 d, volume r² = 0.78, concentration r² = 0.18; HT 2 d, volume r² = 0.89, concentration r² = 0.22; ST 2 d, volume r² = 0.90, concentration r² = 0.05). Similar observations have been previously reported with pesticide loads in runoff from agricultural crops [19]. This greater association of pesticide load with runoff volume explains in part the increased pesticide transport associated with the ST plots compared to HT plots and the increased difference in pesticide loads between cultivation practices at 2 d compared to 63 d.

Plots receiving HT core cultivation had reduced percentage of applied pesticides transported in the runoff relative to the ST plots, with the exception of chlorpyrifos at 63 d after core cultivation (Fig. 5 A and B). The insecticide chlorpyrifos had the smallest percentage of applied active ingredient in the runoff (<2%), followed by the fungicide flutolanil (<10%). The herbicides dicamba, MCPP, and 2,4-D ranged from 13 to 25%, 12 to 28%, and 19 to 35%, respectively, depending on

![Fig. 3. Chemographs and cumulative loads of pesticides measured in runoff from turf plots treated with dicamba (A), flutolanil (B), mecoprop-p (MCPP) (C), 2,4-dichlorophenoxyacetic acid (2,4-D) (D), and chlorpyrifos (E), and managed with solid tines or hollow tines 63 d prior to simulated precipitation and runoff.](image-url)
the cultivation practice. Ma et al. [36] reported runoff from bermudagrass plots managed as a fairway contained 15, 10, and 9% of applied dicamba, mecoprop, and 2,4-D, respectively. Smaller quantities (<3%) of imidacloprid, 2,4-D, cyanazine, and sulfometuronmethyl were reported in the studies of Armbrust and Peeler [37] and Wauchope et al. [31]. The larger percentage of applied herbicides measured with runoff in the present study is most likely related to the greater soil moisture prior to pesticide application. This is consistent with the observations of Cole et al. [30], who found greater runoff losses of chlorpyrifos, dicamba, mecoprop, and 2,4-D when precipitation had preceded applications of pesticides to turf compared to applications following drier periods.

Hollow tine core cultivation removed the cores and returned the soil back to the turf, while ST core cultivation pushed the soil aside to create the channels. As a result, one would anticipate greater soil compaction with the ST cultivation and increased accessibility of soil adsorptive sites with the HT cultivation. This would influence hydraulic conductivity and infiltration as previously reported [18,22,23] as well as pesticide availability for transport [28,38,39]. The percentage of applied pesticides observed in the runoff is also influenced by the physical and chemical properties of the active ingredient. Chemical degradation was not influential in the present study as the time from chemical application

![Fig. 4. Chemographs and cumulative loads of pesticides measured in runoff from turf plots treated with dicamba (A), flutolanil (B), mecoprop-p (MCPP) (C), 2,4-dichlorophenoxyacetic acid (2,4-D) (D), and chlorpyrifos (E), and managed with solid tines or hollow tines 2 d prior to simulated precipitation and runoff.](image)

![Fig. 5. Mean percentage of applied chlorpyrifos, dicamba, flutolanil, mecoprop-p (MCPP), and 2,4-dichlorophenoxyacetic acid (2,4-D) measured in runoff from turf plots managed with solid tines or hollow tines 63 d (A) and 2 d (B) prior to simulated precipitation and runoff. Error bars represent the standard deviation of the mean. Means that do not share the same lowercase letter are statistically different (p < 0.05).](image)
to runoff (30 ± 8 h) was much less than the reported half lives of the compounds of interest (5 to 320 d) (Table 1).

**Cultivation to reduce risk of pesticides**

Estimated environmental concentrations (EEC) of pesticides in a surface water (440,000 L) receiving runoff from fairway turf (1,862 m²) managed with HT or ST resulted in 1.0 to 3.0 μg/L of chlorpyrifos, 13 to 24 μg/L of dicamba, 55 to 123 μg/L of flutolanil, 12 to 20 μg/L of MCPP, and 7 to 10 μg/L of 2,4-D. Specific concentrations for the type of core cultivation (ST, HT) are provided in Figure 6. These EECs were compared with published toxicological endpoints for 19 aquatic organisms including fish, amphibians, mollusks, crustaceans, aquatic plants, and algae (Table 2). Toxicological endpoints included the median lethal concentration (LC50) and median effective concentration (EC50), or the concentration of a compound that results in the measured effect in 50% of the organisms during a defined exposure period. Pesticide levels in a surface water receiving runoff from turf managed with ST exceeded the LC50s or EC50s for nine of the 19 evaluated aquatic organisms. With two exceptions (chlorpyrifos at 63 d and 2,4-D at 63 d), replacing ST core cultivation with HT core cultivation reduced surface water concentrations of chlorpyrifos to levels below the LC50 or EC50 for three fish (M, N, O), MCPP to levels below the EC50 of a diatom (B), and 2,4-D to levels below the EC50 of an aquatic plant (I) (Fig. 6). The sensitivity of rainbow trout (P), opossum shrimp (J), and a water flea (K) to chlorpyrifos and the water flea (K) to 2,4-D was great enough that estimated surface water levels exceeded the LC50s or EC50s regardless of the turf cultivation practice (ST, HT). Likewise, changes in management practice did not significantly influence the risk of pesticides to nonsensitive organisms (e.g., organisms where the LC50 is well above the maximum concentration estimated in the diluted surface water) (Table 2, D–F, Q–R; data not shown on Fig. 6). The toxicity of compounds to organisms can be evaluated using sublethal effects such as induction of enzyme systems, behavioral traits, or reproductive and developmental effects, which are often more sensitive than the more common end point of lethality [40]. The impact of HT core cultivation to reduce pesticide transport with runoff from fairway turf relative to ST core cultivation will be further evident when more sensitive toxicological endpoints are evaluated.

**CONCLUSIONS**

Runoff from managed turf may contain pesticides that contribute to contamination of receiving surface waters. In the present study, runoff volumes and pesticide loads (chlorpyrifos, dicamba, flutolanil, MCPP, or 2,4-D) transported in runoff were reduced when bentgrass fairway turf was managed with HT core cultivation rather than ST core cultivation. The greatest difference between treatments (ST, HT) was observed at 2 d following cultivation compared to 63 d following cultivation. Plots receiving HT core cultivation showed a 15 to 24% reduction in pesticide transport with runoff at 63 d and a 35 to 57% reduction at 2 d following core cultivation. Estimated environmental concentrations of the pesticides in a surface water receiving runoff from turf managed with HT core cultivation exceeded the LC50s or EC50s of nine aquatic organisms including fish, crustaceans, algae, and an aquatic plant. With a few exceptions, replacing ST core cultivation with HT core cultivation reduced surface water concentrations of the pesticides to levels below the LC50 or EC50 of these aquatic organisms, lessening risk associated with pesticides in runoff.
from the fairway turf. Results of the present research provide quantitative information that will allow for informed decisions on cultural practices that can reduce pesticide transport with runoff from turf to minimize exposure to surrounding nontarget areas.

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REFERENCES


Table 2. Median lethal concentrations (LC50) or median effective concentrations (EC50) of selected pesticides

<table>
<thead>
<tr>
<th>Figure letterb</th>
<th>Scientific name</th>
<th>Common name</th>
<th>Exposure (d)</th>
<th>Chlorpyrifos</th>
<th>Dicamba</th>
<th>Flutolanil</th>
<th>MCPPc</th>
<th>2,4-Dd</th>
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<tbody>
<tr>
<td>A</td>
<td>Anabaena flosaquae</td>
<td>Blue-green algae</td>
<td>5</td>
<td>—e</td>
<td>61f</td>
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<td>800f</td>
<td>240f</td>
<td>2,020f</td>
</tr>
<tr>
<td>D</td>
<td>Xenopus laevis</td>
<td>African clawed frog</td>
<td>4</td>
<td>234b</td>
<td>—</td>
<td>—</td>
<td>245,000b</td>
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<tr>
<td>E</td>
<td>Limnodynastes peronii</td>
<td>Brown striped frog</td>
<td>4</td>
<td>—</td>
<td>106,000</td>
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</tr>
<tr>
<td>F</td>
<td>Rana brevipoda porosa</td>
<td>Frog</td>
<td>2</td>
<td>—</td>
<td>—</td>
<td>10,000</td>
<td>—</td>
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</tr>
<tr>
<td>G</td>
<td>Lemna aequinoctiales</td>
<td>Duckweed</td>
<td>7</td>
<td>—</td>
<td>75f</td>
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</tr>
<tr>
<td>H</td>
<td>Potamogeton pectinatus</td>
<td>Sago pondweed</td>
<td>0.13</td>
<td>—</td>
<td>—</td>
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<tr>
<td>J</td>
<td>Americanysis bahia</td>
<td>Opossum shrimp</td>
<td>4</td>
<td>0.04</td>
<td>—</td>
<td>130</td>
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<td>Daphnia pulex</td>
<td>Water flea</td>
<td>1</td>
<td>0.17b</td>
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<td>—</td>
<td>—</td>
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<td>Streptoccephalus sudanicus</td>
<td>Fairy shrimp</td>
<td>2</td>
<td>3.48</td>
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<td>—</td>
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<tr>
<td>M</td>
<td>Cyprinus carpio</td>
<td>Common carp</td>
<td>2</td>
<td>2.8</td>
<td>—</td>
<td>2,900</td>
<td>—</td>
<td>5,800</td>
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<tr>
<td>N</td>
<td>Leponis macrochirous</td>
<td>Bluegill</td>
<td>4</td>
<td>1.7</td>
<td>50,000</td>
<td>5,400</td>
<td>92,000</td>
<td>180,000</td>
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<tr>
<td>O</td>
<td>Oncorhynchus kisutch</td>
<td>Silver salmon</td>
<td>7</td>
<td>1.96f</td>
<td>—</td>
<td>—</td>
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</tr>
<tr>
<td>P</td>
<td>Oncorhynchus mykiss</td>
<td>Rainbow trout</td>
<td>4</td>
<td>1</td>
<td>28,000</td>
<td>5,400</td>
<td>10,000</td>
<td>110,000</td>
</tr>
<tr>
<td>Q</td>
<td>Aplexa hypnorum</td>
<td>Snail</td>
<td>4</td>
<td>806</td>
<td>—</td>
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<td>R</td>
<td>Crassostrea gigas</td>
<td>Pacific oyster</td>
<td>9</td>
<td>—</td>
<td>—</td>
<td>4,200</td>
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<tr>
<td>S</td>
<td>Crassostrea virginica</td>
<td>American oyster</td>
<td>4</td>
<td>84f</td>
<td>—</td>
<td>1,500f</td>
<td>—</td>
<td>58,700f</td>
</tr>
</tbody>
</table>

— Letters referenced in Figure 6. LC50 for organisms E, F, J, M, N, P–R, and EC50 for organisms A–D, G–I, K, L, O, and S.
— MCPP = mepocyp-p.
— 2,4-D = 2,4-dichlorophenoxyacetic acid.
— — = No data.
— Effect measured for EC50 = population abundance.
— Effect measured for EC50 = population changes.
— Effect measured for EC50 = abnormal growth and development.
— Effect measured for EC50 = growth rate.
— Effect measured for EC50 = photosynthesis.
— Effect measured for EC50 = immobile (intoxication).
— Effect measured for EC50 = smell/sniff (behavior).
Cultivation to reduce risk of pesticide runoff from turf