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Evaluation of nitrogen and phosphorus transport with runoff from fairway turf managed with hollow tine core cultivation and verticutting☆

Pamela J. Rice [a,*], Brian P. Horgan [b]

[a] *U.S. Department of Agriculture, Agricultural Research Service, 1991 Upper Buford Circle, St. Paul, MN 55108, USA*
[b] *Horticulture Department, University of Minnesota, St. Paul, MN 55108, USA*

HIGHLIGHTS

- We compared runoff from turf managed with hollow tines (HT) or HT and verticutting.
- We hypothesized verticutting would further reduce fertilizer transport with runoff.
- Alteration of risk associated with changes in management practices was not observed.
- Water quality limits for phosphorus were exceeded in ponds receiving the turf runoff.
- Levels of nitrogen in a pond receiving runoff were below surface water standards.

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ABSTRACT

Enrichment of surface waters with excess nutrients is associated with increased algal blooms, euthrophication and hypoxic zones, as reported in the northern Gulf of Mexico. A source of nutrients to surface waters results from fertilizer runoff. Management strategies used to maintain turf on golf courses and recreational fields often include aerification and application of fertilizer. Although research exists on benefits of core cultivation and verticutting (VC) to reduce thatch and the transport of applied chemicals with runoff, there are no studies reporting the effect of coupling these management practices with the goal of further reduction of off-site transport of fertilizer with runoff. We hypothesized that the addition of VC to hollow tine core cultivation (HTCC) would enhance infiltration of precipitation, reduce runoff and nutrient transport with runoff and therefore influence concentrations of nutrients in surface waters receiving runoff from turf managed as a golf course fairway. Greater runoff and mass of soluble phosphorus and ammonium nitrogen transported with runoff were measured from plots managed with HTCC + VC than HTCC; however, the reverse was noted for nitrate nitrogen. Only a portion of the observed trends proved to be statistically significant. Our research showed no reduction or enhancement of risk associated with surface water concentrations of phosphorus or nitrogen, resulting from runoff from creeping bentgrass turf that was managed with HTCC + VC compared to HTCC. Data obtained in this research will be useful to grounds superintendents when selecting best management practices and to scientists seeking data relating runoff to land management for watershed-scale modeling.

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1. Introduction

Managed turf is found in both public and private settings; in parks and cemeteries, along road sides and right-of-ways, as residential and commercial lawns, as sod farms, and on athletic fields and golf courses. In the United States an estimated 16 million hectares of land is covered by tended lawn (Milesi et al., 2005). There are an estimated 35,000 golf courses worldwide with the approximately 17,000 golf courses in the United States, more than 2,300 golf courses in either Canada, the United Kingdom or Japan, and approximately 1,500 golf courses in Australia (Saito, 2010).

Nitrogen and phosphorus are important plant nutrients that are often applied to highly managed biotic systems, including golf course turf. Approximately one-third of a typical golf course is comprised of fairways (Lyman et al., 2007; Watson et al., 1992). 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. Shuman (2002) observed that the mass of phosphorus in runoff from golf course fairway turf was directly related to the

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Abbreviations: (HTCC), hollow tine core cultivation; (NCC), no core cultivation; (STCC), solid tine core cultivation; (VC), verticutting.

☆ Reference to specific products does not imply endorsement by U.S. Department of Agriculture or the University of Minnesota to the exclusion of other suitable products.

* Corresponding author at: U.S. Department of Agriculture — ARS, 1991 Upper Buford Circle, Borlaug Hall, Room 439, St. Paul, Minnesota 55108, USA. Tel.: +1 612 624 9210; fax: +1 651 649 5175.

E-mail addresses: pamela.rice@ars.usda.gov (P.J. Rice), bphorgan@umn.edu (B.P. Horgan).

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fertilizer rate with the initial runoff event containing the majority of the transported phosphorus. 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.

The presence of excess nutrients in surface waters may be harmful to lake biota and human health when at levels that produce undesirable consequences such as eutrophication or harmful algal blooms (Correl, 1998; Lake Scientist, 2012). In addition, nitrate has been suspected to be an ecologically relevant endocrine disruptor that can alter hormone regulation, causing morphological abnormalities (Guillette and Edwards, 2005). When found in drinking water, nitrate exposure may result in methemoglobinemia, a potentially lethal condition known as blue baby syndrome (Knobeloch et al., 2000; United States Environmental Protection Agency, 1986). To combat these concerns, water quality guidelines have been proposed to limit phosphorus and nitrogen concentrations in surface waters. For example, criteria have been established to limit total phosphorus concentrations to 0.025 mg L^{-1} within lakes or reservoirs, 0.05 mg L^{-1} in streams draining into lakes or reservoirs and 0.1 mg L^{-1} in streams or flowing waters not directly discharging into lakes or reservoirs (Schindler, 1977; United States Environmental Protection Agency, 1986). Nitrate nitrogen water quality standards have recently been proposed for surface waters that support aquatic life and recreation (class 2). These draft standards are based on aquatic life toxicity test reported in the scientific literature and completed by the by the U.S. Environmental Protection Agency. The acute standard (maximum concentration at any time) has been set at 41 mg L^{-1} NO_3–N. Chronic standards (four day average concentrations that can not be exceeded more than once in a three year period) have been set at 3.1 mg L^{-1} NO_3–N (class 2A — cold water community) and 4.9 mg L^{-1} NO_3–N (class 2B — cool-warm water community); levels that are more restrictive than the existing drinking water standard for human health set at 10 mg L^{-1} NO_3–N (United States Environmental Protection Agency, 1986; Monson, 2010; MPCA, 2010).

Recreational fields and golf courses and are subject to foot and vehicle traffic; resulting in turf wear, soil compaction and reduced water infiltration (Dunn et al., 1995; Baldwin et al., 2008). These green spaces are often managed to alleviate surface compaction, enhance water penetration, stimulate root and shoot growth and control thatch (Barton et al., 2009; Beard, 1973; Callahan et al., 1998; Carrow et al., 1987; Dunn et al., 1995; Rowland et al., 2009; Turgeon, 1985; Vargas and Turgeon, 2004; White and Dickens, 1984). While thatch is beneficial to enhance turf durability, moderate soil temperatures and lessen weed invasion, an excessive thatch-mat can increase disease and pest pressure, lessen cold temperature tolerance, and reduce water infiltration and hydraulic conductivity (Beard, 1973; White and Dickens, 1984; Murray and Juska, 1977; Harris, 1978; Miller, 1965). Verticutting (VC) and core cultivation are two management practices used to remove excess thatch on sports fields and golf course fairways and putting greens (Barton et al., 2009; Stier and Hollman, 2003). Core cultivation with hollow tines (HTCC) removes cores from the turf, which are deposited on the turf surface and allowed to air-dry before the soil is brushed back into the open holes and the extracted thatch is removed. Verticutting uses rotating blades to slice into the turf to remove dead plant material and thatch, promoting new turf growth and preparing seedbeds for overseeding. Core cultivation or verticutting of turfgrass promotes water conservation as these management strategies increase water movement into the turfgrass root zone; resulting in greater infiltration of rainfall, enhanced rooting depth that reduces water leaching beyond the root zone, and healthier turf that requires less water and need for pest control (Waltz, 2007). The frequency of these practices (two to three times a year or as often as every 10 days) and their associated cost will vary with turfgrass species and weather conditions, as they are typically performed when the turfgrass is growing and not under stress (e.g. spring and fall) (Torisello, 2007).

Evaluation of runoff and the transport of nutrients, plant protection products and soil with runoff has been documented around the world at multiple scales; including plot-, field-, watershed- and catchment-scale monitoring and modeling (Cohen et al., 1999; Soulsby et al., 2004; Nash et al., 2005; Xu et al., 2007; Bakri et al., 2008; Vadas et al., 2008; Thomaz and Vestena, 2012; Donn et al., 2012; Pärn et al., 2012). For example, in Australia, moderate to high levels of nitrogen and phosphorus were measured in a catchment with noted increases in nutrients occurring as the stormwater passed through the urban areas (Bakri et al., 2008). A modeling assessment of runoff in a watershed in Brazil showed adoption of conservation practices that increased water infiltration would reduce runoff and total nitrogen and total phosphorus transported with the runoff (Rocha et al., 2012). Plot- and field-scale research has documented the influence of management and cultural practices on runoff and chemical transport with runoff from highly managed biotic systems, including turfgrass (Wauchope et al., 1990; Cole et al., 1997; Kauffman and Watschke, 2007; Rice et al., 2010; Rice and Horgan, 2011; Rice et al., 2011) and agricultural crops (Hansen et al., 2001; Potter et al., 2004; Rice et al., 2007). In addition, reduced surface runoff has been observed from turfgrass compared to tilled soils (Gross et al., 1990) and from creeping bentgrass (*Agrostis palustris* Huds.) turf relative to perennial ryegrass (*Lolium perenne* L.) turf (Linde et al., 1995). Documenting and adopting practices that reduce the off-site transport of nutrients and pesticides with overland flow or runoff will help maintain plant nutrient or protection products at their site of application, therefore enhancing efficacy while reducing contamination and unintended affects in adjacent areas.

The objective of the present study was to identify which cultural practice, hollow tine core cultivation (HTCC) or HTCC with verticutting (HTCC+VC), maximizes phosphorus and nitrogen retention at the site of fertilizer application, thereby maintaining turf quality while minimizing adverse environmental effects associated with the off-site transport of nutrients. Edge-of-plot runoff and the concentration of soluble phosphorus (sol-P), ammonium nitrogen (NH_4–N), and nitrate nitrogen (NO_3–N) in the runoff were measured to determine the mass load of nutrients transported with runoff. Estimated environmental concentrations of phosphorus and nitrogen in a surface water receiving runoff from turf were calculated using our plot load data and reported runoff area and pond volumes measured at a local golf course. These surface water concentrations were compared with water quality criteria to determine which management practice is most efficient at mitigating environmental risk.

2. Materials and methods

2.1. Turf plots, runoff collection system and rainfall simulator

Experiments were conducted at the University of Minnesota (Saint Paul, MN, USA) on turf plots (6 plots; individual plot size: 148.8 m^2, 24.4 m length × 6.1 m width) managed as a golf course fairway. *A. palustris* Huds. (L-93 creeping bentgrass) covered Waukegan silt loam (3% organic carbon, 29% sand, 55% silt, and 16% clay) that was graded to a 4% slope running east to west. Runoff collection systems, described in detail elsewhere (Rice et al., 2010), were constructed at the western edge of each plot. In short, stainless steel flashing guided runoff from each turf plot into a polyvinyl chloride (PVC) gutter which led to a stainless steel trapezoidal flume (Plasti-Fab, Tualatin, OR, USA) equipped with bubble tube and sample collection ports. Gutter covers and flume shields prevented dilution of runoff with precipitation.

A rainfall simulator, modified from the design of Coody and Lawrence (1994), was constructed to delivered precipitation with a droplet size spectrum and impact velocity similar to natural rainfall. The base of the simulator surrounded two plots and guided water to eighteen risers 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. Specific details of the rainfall simulator are published elsewhere (Rice et al., 2010).

2.2. Turf management

Creeping bentgrass 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.

Fifteen days (15 ± 1 days) prior to simulated precipitation and collection of runoff, 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 dry and worked back into the turf. A back-pack blower and leaf rake removed the turf and thatch from the plot surface. Seven days following core cultivation, three of the six plots were verticut with 1 mm blades (spaced 3.8 cm apart, slicing to a 1.9 cm depth) (Turfco TriWave Overseeder, Turfco Manufacturing Inc., Blaine, MN).

2.3. Fertilizer

Granular fertilizer, Plant Nutrient 18-3-18 (Agriliance, Inver Grove Heights, MN, USA), 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 across all plots simultaneously in a direction perpendicular to runoff flow (direction of application passes: alternating from south to north and north to south; direction of runoff flow: west to east) at a rate of 136.5 kg ha^{-1}, which was followed by brief irrigation (<1 mm) with the maintenance irrigation system. No additional irrigation or precipitation occurred between completion of the fertilizer application and initiation of simulated precipitation.

2.4. Simulated precipitation

Forty-eight hours prior to initiation of simulated precipitation each plot was pre-wetted beyond soil saturation to ensure uniform water distribution and allow for collection of background runoff samples. 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. Petri dishes (glass, 14-cm) were distributed across the plots to verify delivery and application rates. Plastic sheeting and Petri dishes were removed following chemical application (14.5 ± 3.2 h prior to simulated precipitation) and 12-cm rain gauges (Taylor Precision Products, Las Cruces, NM) were distributed throughout each plot to quantify precipitation. Within 3 h prior to initiation of simulated precipitation soil moisture was measured with a soil moisture meter (Field Scout TDR 300, Spectrum Technologies, Plainfield, IL). Wind speeds were measured on-site with a hand-held meter (Davis Instruments, Hayward, CA, USA) and simulated precipitation was initiated once wind speeds dropped below 2 m s^{-1}, preventing precipitation drift as a result of high wind speeds. 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 during runoff events showed no water movement between plots. Simulated precipitation events (duration: 1.9 ± 0.1 h, rate: 39 ± 3 mm h^{-1}) represented storm intensities recorded in Minnesota, USA, during July through October with recurrence interval of 25 years (Huff and Angel, 1992).

2.5. Runoff collection and analysis

An automated flow meter (Isco model 730, Lincoln, NE, USA) and runoff sampler containing 24, 350-ml glass bottles (ISCO model 6700) recorded runoff flow rates every minute, calculated total runoff volumes and collected time-paced (5 min) runoff samples from each plot. Water samples were removed from the automated samplers and stored at −20 °C respectively, until laboratory measurement. Runoff water collected from the turf plots 48 h prior to chemical application and water collected from the water source supplying the rainfall simulator served as runoff water and irrigation water matrix samples. Matrix samples spiked with known quantities of the applied chemicals served as positive control samples.

Water samples were analyzed for soluble phosphorus (sol-P), ammonium nitrogen (NH_4–N), and nitrate nitrogen (NO_3–N). 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).

2.6. Calculation of nutrient loads with runoff and nutrient concentrations in receiving surface waters

Nutrient loads (L_N, mg m^{-2}) transported with runoff for each time point were calculated by $L_N = \Sigma\ (C_N \bullet R \bullet T)/A_P$ considering measured nutrient concentration (C_N, mg L^{-1}) in the filtered runoff water, flow rate (R, L min^{-1}) at time of sampling, time (T, min) between samples and area (A_P, m^2) of the turf plot. Concentrations of nutrients in a surface water receiving runoff from fairway turf were calculated using information from a golf course, located less than 20 miles from the study site, characterizing the area of turf contributing to overland flow and dimensions of a pond receiving the runoff (http://www.pca.state.mn.us/publications/stormwaterresearch-eaglelake.pdf, pond 4 sub-watershed). Using this scenario, nutrient concentrations in a receiving surface water (S_{NC}, mg L^{-1}) were calculated by $S_{NC} = (L_N \bullet (A_{GC} \bullet P_{FT}))/S_V$ considering nutrient loads in the edge-of-turf runoff (L_N, mg m^{-2}), area of the golf course (A_{GC}, 5641 m^2) contributing runoff to the receiving surface water, the estimated percentage of the golf course represented by fairway turf (P_{FT}, 0.33 or 33%) (Lyman et al., 2007; Watson et al., 1992), and the volume (S_V, 440,000 L) of the receiving surface water (Rice and Horgan, 2011). Nutrient concentrations of the surface water were compared to water quality criteria and drinking water standards to evaluate which management plan is the most efficient at mitigating environmental risk.

2.7. Statistical analysis

The rainfall simulator was limited to delivering precipitation to two of the six plots concurrently; requiring the runoff event to be completed in three parts. As a result, a randomized complete block design was used to assign one of each evaluated management practices to a block, providing three replicate side-by-side comparisons for each runoff event and eliminating potential variability introduced by the rainfall simulator. Calculation of F-ratios (0.05) showed homogeneity of variance between management practices within a runoff event and across runoff events (http://www.acastat.com/Statbook/fratio.htm). Analyses of variance were performed to evaluate runoff volumes and nutrient loads, with management practices as the single criteria of classification for the data. Statistical significance between treatment means was confirmed by least significant difference (LSD, 0.05 = error degrees of freedom and 0.05 probability to determine two-tailed t values). Coefficients of determination (r^2) were calculated to determine the proportional importance of runoff volume and chemical concentration to chemical load (Steel et al., 1997).

3. Results

3.1. Simulated precipitation and runoff volume

Replicated runoff experiments were conducted October 4–5, 2006 (event-1) and August 11–12, 2009 (event-2), while the turf was actively growing (air temperatures max/min: 24 °C/11 °C, event-1; 31 °C/17 °C, event-2). Simulated precipitation was initiated 15.3 ± 2.7 h (event-1) and 13.7 ± 3.6 h (event-2) following the application of the fertilizer and terminated 90 min after the onset of runoff. Soil moisture, precipitation depth and precipitation rates are presented in Table 1. Hydrographs and cumulative runoff volumes representing the average of treatment replicates for each runoff event are provided in Fig. 1A and B. Comparison of runoff measurements along the hydrograph shows greater runoff from HTCC+VC than HTCC for 68 ± 22% (53 ± 22% significant at 5%) of the samples. Overall, cumulative runoff measured from plots receiving HTCC were 10% and 11% less than plots managed with HTCC+VC; however, the difference in cumulative runoff between management practices was not statistically significant (event-1: HTCC = 25.8 ± 1.2 L m^{-2} (mm), HTCC+VC = 28.7 ± 3.0 L m^{-2} (mm); event-2: HTCC = 26.2 ± 6.4 L m^{-2} (mm), HTCC+VC = 29.3 ± 1.6 L m^{-2} (mm)). The percentage of applied precipitation as runoff from turf managed with HTCC (36 ± 1.7%) or HTCC+VC (38 ± 0.4%), 2 days after saturation to field capacity, is in line with the findings of Shuman (2002) where 37 to 44 % of applied precipitation (50 mm) was reported as runoff from fairways of Tifway bermudagrass (*Cynodon dactylon* (L.) Pers.), 2 days following irrigation to field capacity.

3.2. Nutrient transport with runoff

The off-site transport of nutrients with runoff from plots managed with hollow tine core cultivation, with or without verticutting, was evaluated using edge-of-plot chemical loads calculated from measured runoff and chemical concentrations (mg L^{-1}) in the runoff. Analysis of the source water applied as maintenance irrigation and simulated precipitation contained negligible levels of nutrients (sol-P, NH_4–N and NO_3–N = 0.001 to 0.005 mg L^{-1}), which were subtracted from the concentrations measured in the runoff. Soluble phosphorus, NH_4–N, and NO_3–N were detected in the initial runoff sample and throughout the runoff events. The minimum, median and maximum concentrations measured in the edge of turf runoff for all replications in the two runoff events ($n > 550$) were as follows: HTCC (sol-P) = 0.18, 0.57 and 1.67 mg L^{-1}; HTCC+VC (sol-P) = 0.15, 0.58 and 1.96 mg L^{-1}; HTCC (NH_4–N) = 0.28, 0.60 and 5.39 mg L^{-1}; HTCC+VC (NH_4–N) = 0.28, 0.65 and 6.84 mg L^{-1}; HTCC (NO_3–N) = 0.09, 0.34 and 0.94 mg L^{-1}; HTCC+VC (NO_3–N) = 0.05, 0.27 and 0.87 mg L^{-1}. Chemographs of nutrient loads and cumulative loads of the applied nutrients are presented in Fig. 1C–H. Comparison of runoff samples represented in the chemographs showed HTCC+VC resulted in greater loads than HTCC in 77 ± 7% (54 ± 18% significant at 5%) of the sol-P samples (Fig. 1C and D) and 80 ± 12% (69 ± 20% significant at 5%) of the NH_4–N samples (Fig. 1E and F). Nitrate nitrogen (NO_3–N) loads were greater from HTCC than HTCC+VC in 64 ± 6% (51 ± 25% significant at 5%) of the samples (Fig. 1G and H). With the exception of NO_3–N, the total mass of chemicals transported with runoff (cumulative load) from plots managed with HTCC+VC exceeded that of plots managed with HTCC. Runoff from plots receiving HTCC+VC contained 4% and 33% greater loads of sol-P (Fig. 1C) and NH_4–N (Fig. 1E) for event-1 and 20% and 14% greater loads of sol-P (Fig. 1D) and NH_4–N (Fig. 1F) for event-2 than plots managed with HTCC. A reverse trend was noted for NO_3–N where 10% and 31% greater loads were measured in runoff from plots managed with HTCC (Fig. 1G and H). However, statistical analysis of sol-P, NH_4–N and NO_3–N cumulative loads for HTCC versus HTCC+VC revealed only NH_4–N in event-1 (Fig. 1E) was statistically significant. Evaluation of a larger number of runoff events may reveal greater statistical significance between these management practices. For both management practices (HTCC and HTCC+VC) the off-site transport of applied nutrients with runoff were attributed to runoff volume more than nutrient concentrations in the runoff (HTCC, volume $r^2 = 0.72$, concentration $r^2 = 0.12$; HTCC+VC, volume $r^2 = 0.68$, concentration $r^2 = 0.40$).

Table 1
Soil moistures, precipitation depths and precipitation rates measured for the runoff events.

		Precipitation	
	Soil moisture (%)[a,b]	Depth (mm)[a]	Rate (mm h^{-1})[a]
Runoff event – 1	41 ± 3	75 ± 7	37 ± 2
Runoff event – 2	41 ± 2	75 ± 7	40 ± 2

[a] Data presented as the mean ± standard deviation (soil moisture $n = 27$, precipitation $n = 36$).

[b] Percentage water holding capacity 3h prior to simulated precipitation.

3.3. Nutrient concentrations in a surface water receiving turf runoff

Regardless of the management practice evaluated (HTCC or HTCC+VC), the range of concentrations of sol-P measured in the undiluted runoff, and projected to occur as diluted concentrations in a pond receiving the runoff, exceeded guidelines to limit eutrophication (total phosphorus guidelines: 0.025 and 0.05 mg L^{-1}) (Schindler, 1977; United States Environmental Protection Agency, 1986); runoff: 0.18 to 1.67 mg L^{-1} (HTCC) and 0.15 to 1.96 mg L^{-1} (HTCC+VC); pond: 0.056 mg L^{-1} (HTCC) and 0.063 mg L^{-1} (HTCC+VC) (Fig. 4). The reverse was true for both management practices (HTCC or HTCC+VC) with NO_3–N concentrations where measured runoff concentrations (HTCC: ≤0.94 mg L^{-1}, HTCC+VC: ≤0.87 mg L^{-1}) and projected pond concentrations (HTCC: 0.03 mg L^{-1}, HTCC+VC: 0.02 mg L^{-1}) remained below proposed NO_3–N standards for surface waters (chronic exposure standards 3.1 and 4.9 mg L^{-1}for cold and cool-warm water communities) (Monson, 2010; MPCA, 2010) (Fig. 4). Although the addition of verticutting may enhance turf health and quality, our results suggest the addition of VC to HTCC has minimal influence on the quantity of nutrients transported with runoff and associated risks to adjacent surface waters.

4. Discussion

In previous studies we compared individual management practices for their ability to reduce runoff volumes and the off-site transport of applied compounds with runoff from turf managed as a golf course fairway (Rice and Horgan, 2011; Rice et al., 2011). These studies revealed reduced runoff volumes with hollow tine core cultivation (HTCC) compared to no core cultivation (NCC) (Fig. 2A), solid tine core cultivation (STCC) (Fig. 2B) and verticutting (VC) (Fig. 2C). We speculated the coupling of VC with HTCC would enhance infiltration beyond what was accomplished by each practice individually. For the four individual management practices (NCC, HTCC, STCC, VC), the off-site transport of applied nutrients with runoff were attributed to runoff volume more than nutrient concentrations in the runoff (HTCC, volume $r^2 = 0.78$, concentration $r^2 = 0.27$; VC, volume $r^2 = 0.86$, concentration $r^2 = 0.65$; STCC, volume $r^2 = 0.89$, concentration $r^2 = 0.16$; NCC, volume $r^2 = 0.54$, concentration $r^2 = 0.15$). Therefore we also expected to find reduced off-site transport of nutrients with the coupled management practices. Measured data from the present study comparing HTCC with HTCC+VC (Fig. 3A and B) and an additional study comparing VC with HTCC+VC (Fig. 3C) revealed this was not true. In fact, with one exception with NO_3–N (Fig. 3B), a similar or greater percentage of the applied precipitation and nutrients were observed in the combined management practice (HTCC+VC). Considering both the combined and individual management practices (HTCC+VC, HTCC,

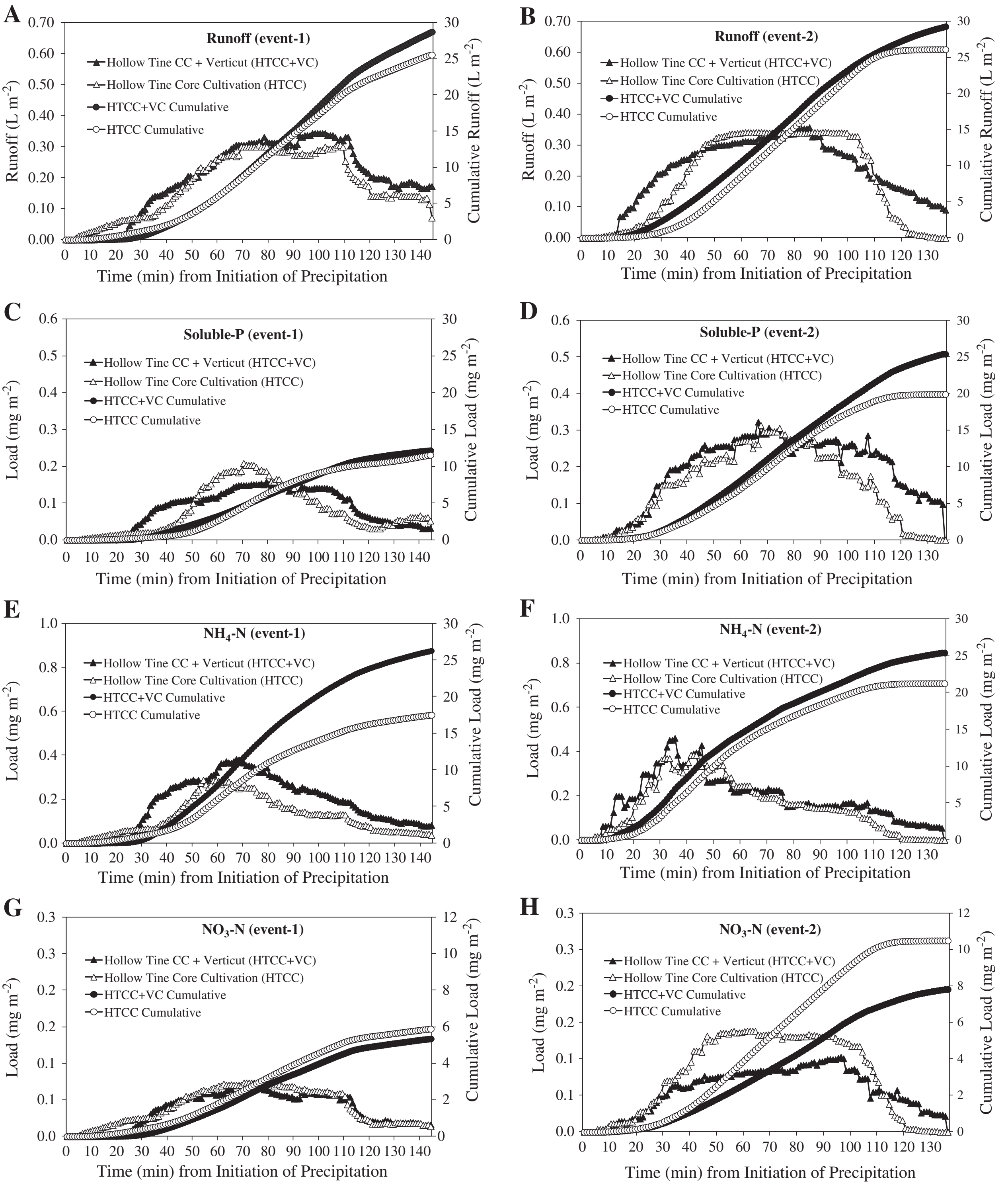

Fig. 1. Hydrographs and cumulative volumes of runoff (A and B) and chemographs and cumulative loads of soluble phosphorus (Soluble-P, C and D), ammonium nitrogen (NH_4-N, E and F), and nitrate nitrogen (NO_3-N, G and H) measured in runoff from turf plots managed with hollow tine core cultivation (HTCC) versus hollow tine core cultivation and verticutting (HTCC + VC).

VC, STCC, NCC) for all runoff events ($n = 6$, Figs. 2 and 3), the average percentage of applied nutrients transported in the runoff were 7 ± 4% sol-P, 8 ± 2% NH_4–N and 11 ± 4% NO_3–N. This is in range with the observation of others where 2 to 15% of applied nutrients were observed in runoff from bermudagrass, creeping bentgrass, or perennial ryegrass with different soil moistures (Gardner et al., 2000; Linde et al., 1995; Shuman, 2002).

Based on the results of the paired comparison studies in the present research and earlier evaluations, turf managed with HTCC had the smallest quantity of runoff followed by, from least to greatest, NCC < VC < HTCC+VC < STCC. This is believed to result from improved infiltration with HTCC as well as a difference in soil compaction when managing turf with VC or STCC. Hollow tine core cultivation removes cores, returning soil to the turf while removing excess thatch. In contrast, STCC and VC displace soil with solid tines and blades, respectively, resulting in localized compaction. Greater porosity and saturated water conductivity in turf managed with HTCC compared to STCC has been reported (Murphy et al., 1992), as well as enhanced water infiltration

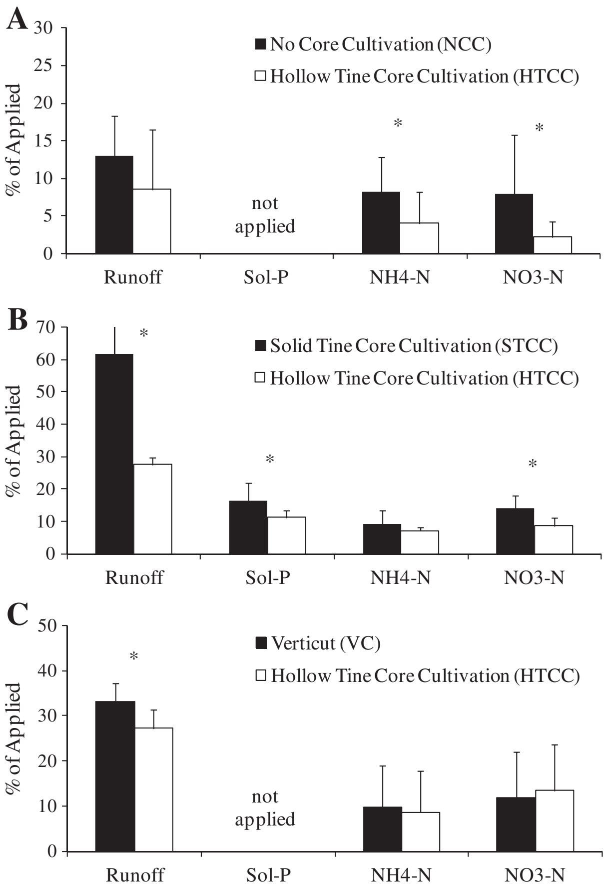

Fig. 2. Side-by-side comparison of management practices. Percentage of applied precipitation as runoff and percentage of applied soluble phosphorus (Sol-P), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) measured in runoff from turf plots managed with (A) hollow tine core cultivation (HTCC) versus no core cultivation (NCC); (B) HTCC versus solid tine core cultivation (STCC); (C) HTCC versus verticutting (VC). Standard deviations of the replicate means are presented as error bars. An asterick above the paired bars denotes a statistical difference ($p<0.05$).

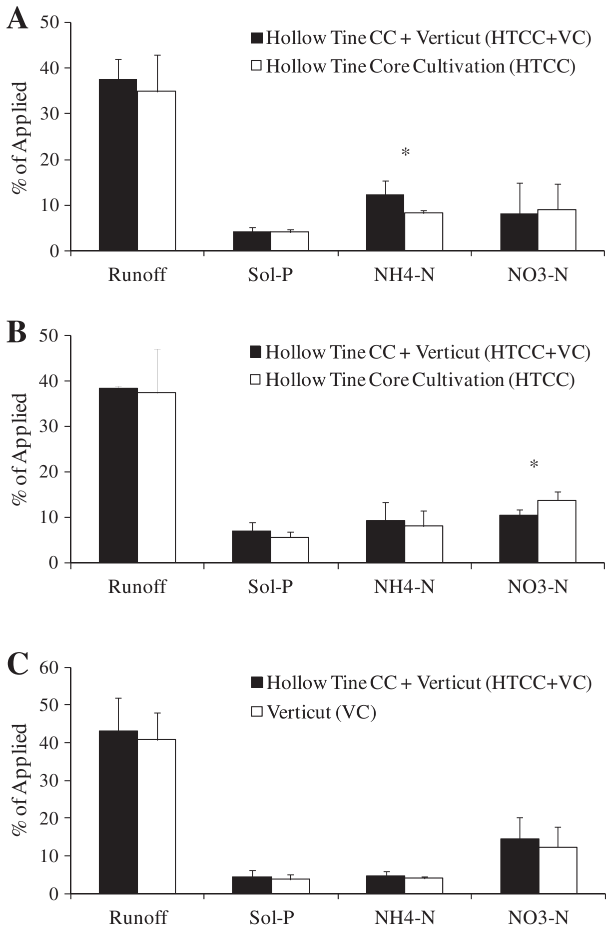

Fig. 3. Side-by-side comparison of management practices. Percentage of applied precipitation as runoff and percentage of applied soluble phosphorus (Sol-P), ammonium nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) measured in runoff from turf plots managed with (A and B) hollow tine core cultivation (HTCC) versus hollow tine core cultivation and verticutting (HTCC + VC) and (C) HTCC + VC versus verticutting (VC). Standard deviations of the replicate means are presented as error bars. An asterick above the paired bars denotes a statistical difference ($p<0.05$).

in turf managed with HTCC compared to untreated turf (Baldwin et al., 2006; McCarty et al., 2007). Solid tine core cultivation has been shown to produce localized compaction with the greatest compaction at the base of the zone of cultivation (Baldwin et al., 2006; Murphy et al., 1992). Hollow tine core cultivation has also been shown to result in compaction along the sidewalls and base of the core channel; however, sidewall compaction diminished while base compaction remained after 95 days (Petrovic, 1979). We suspect that soil compaction resulting from HTCC is less than VC or STCC as the difference in percentage of applied precipitation measured as runoff from turf managed with HTCC was 6% less than VC and 34% less than STCC. It is likely the observation of enhanced runoff and nutrient transport with runoff from the combined management practices (HTCC+VC) relative to each management practice individually (HTCC or VC) is the result of greater soil compaction resulting from the combination of the two practices. A study evaluating infiltration rates in residential lawns noted compaction and soil structure were some of the greatest contributing factors to changes in infiltration (Hamilton and Waddington, 1999). Further study would be required to confirm or disprove our speculation.

As we had seen with the results of the present study, the calculated concentrations of phosphorus and nitrogen in a surface water receiving runoff from fairway turf managed with the individual (HTCC, VC, STCC) or combined (HTCC+VC) management practices exceeded water quality guidelines for phosphorus (Fig. 4) but were below proposed surface water standards for NO_3–N and levels of nitrogen that would enhance algal growth (Fig. 4) (United States Environmental Protection Agency, 1986; Monson, 2010; MPCA, 2010). Our results show there is no significant difference in risk to a surface water receiving nutrient loads with runoff from fairway turf, managed with either HTCC or HTCC+VC, using the mentioned water quality guidelines and proposed standards. If a more sensitive water quality guideline emerges for NO_3–N (e.g. low levels that may influence endocrine disruption in sensitive organisms) an important difference between these management practices may be realized. Considering the levels of phosphorus measured in the runoff, additional management strategies would need to be implemented as observed and calculated concentrations in the runoff and receiving surface water exceeded water quality guidelines for both HTCC and HTCC+VC. It is important to note the results we have reported are, as far as we know, applicable only for the specific conditions evaluated (e.g. precipitation rate, precipitation depth and soil moisture). Variation of precipitation and soil moisture conditions with the same management practices may produce results that differ, as a direct relationship between runoff volume and soil moisture at the time of the precipitation event has been reported (Shuman, 2002). We have also observed, when comparing the effect of management practices to reduce the off-site transport of pesticides with runoff from turf, that percentage of applied precipitation resulting as runoff was influenced by soil moisture ($r^2 = 0.62$) more than precipitation depth ($r^2 = 0.23$) or precipitation rate ($r^2 = 0.06$) (Rice et al., 2011). Others have reported storm direction and speed can affect the shape, peak, and time to peak observed in runoff hydrographs (Yen and Chow, 1969; Sargent, 1981; Jensen, 1984; Seo and Schmidt,

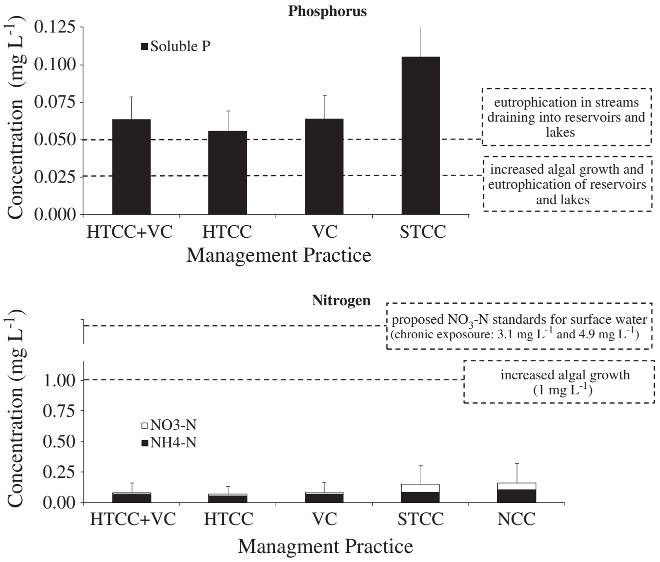

Fig. 4. Estimated environmental concentrations of phosphorus (Soluble P) and nitrogen (nitrate nitrogen (NO$_3$-N) and ammonium nitrogen (NH$_4$-N)) in a surface water receiving runoff from fairway turf managed with hollow tine core cultivation and verticutting (HTCC + VC), hollow tine core cultivation (HTCC), verticutting (VC), solid tine core cultivation (STCC) and no core cultivation (NCC). There is no data for phosporus and NCC as the fertilizer applied during that study did not contain phosphorus. The broken lines represent established water quality criteria and drinking water standards. Split columns in the nitrogen graph represent NO$_3$-N (top) and NH$_4$-N (bottom).

2012). Although the evaluated management practices are almost exclusively used to manage turf and landscapes, any management strategy or daily practice that enhances soil compaction or reduces infiltration of precipitation could result in greater runoff and the transport of chemicals and soil with runoff. This would be applicable to agricultural, residential and construction areas, which have been reported in the literature world-wide (Harden, 1992; Hamilton and Waddington, 1999; Batey, 2009; Boulal et al., 2011; Ehigiator and Anyata, 2011; Franklin et al., 2012; Maetens et al., 2012).

5. Conclusions

In this study and previous studies we have observed that runoff volume contributes more to the overall load and off-site transport of chemicals in runoff from turf than the concentration of the chemicals in the runoff. Therefore we anticipated the addition of VC to HTCC would further enhance infiltration of precipitation and provide an even more effective means of reducing the off-site transport of nutrients to surrounding surface waters. We observed the addition of VC to HTCC (HTCC+VC) reduced infiltration of precipitation, resulting in slightly larger runoff volumes and greater off-site transport of sol-P and NH$_4$–N loads in the runoff. The opposite trend was observed with NO$_3$–N where greater cumulative loads were measured in runoff from turf managed using HTCC without VC. Most of these observed differences were not statistically significant; however, only two runoff events with three replicate plots per management practice were evaluated. We anticipate further statistical significance between management practices may be revealed when a greater number of runoff events are considered.

Evaluation of established and emerging management practices is important in order to understand their efficacy and sustainability. As benefits and improvements in management strategies are discovered they can be implemented, while practices with unexpected adverse consequences can be modified or replaced. Our research results showed no significant reduction or enhancement of risk associated with surface water concentrations of phosphorus or nitrogen, resulting from runoff from golf course fairway turf that was managed with HTCC+VC compared to HTCC. Overall, in contrast to what we had hypothesized, the addition of VC to HTCC did not enhance infiltration of precipitation or the reduction of runoff and nutrient transport with runoff. Data obtained in this research will be useful to grounds superintendents when selecting best management practices and to scientists seeking data relating runoff to land management for watershed-scale modeling (Van Liew et al., 2007).

Conflict of interest statement

There is no conflict of interest.

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References

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

Baldwin CM, Liu H, Brown PJ. Effects of core cultivation tine entry angle on golf putting greens. Hortic Technol 2006;16:265–9.

Baldwin CM, Liu H, McCarty LB. Winter foot and equipment traffic impacts on a "L93" creeping bentgrass putting green. Hortic Sci 2008;43:922–6.

Barton L, Wan GCY, Buck RP, Colmer TD. Effectiveness of cultural thatch-mat controls for young and mature Kikuyu turfgrass. Agron J 2009;101:67–74.

Batey T. Soil compaction and soil management — a review. Soil Use Manag 2009;25:335–45.

Beard JB. Turfgrass: science and culture. New Jersey: Prentice-Hall, Engelwood Cliffs; 1973.

Boulal H, Gomez-Macpherson J, Gomez JA, Mateos L. Effect of soil management and traffic on soil erosion in irrigated annual crops. Soil Tillage Res 2011;115–116:62–70.

Callahan LL, Sanders WL, Parham JM, Harper CA, Lester LD, McDonald ER. Cultural and chemical controls of thatch and their influence on rootzone nutrients in a bentgrass green. Crop Sci 1998;38:181–7.

Carlson RM, Cabrera RI, Paul JL, Quick J, Evans RY. Rapid direct determination of ammonium and nitrate in soil and plant tissue extracts. Commun Soil Sci Plant Anal 1990;21:1519–29.

Carrow RN, Johnson BJ, Burns RE. Thatch and quality of Tifway bermudagrass turf in relation to fertility and cultivation. Agron J 1987;79:524–30.

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

Cole JT, Baird JH, Basta NT, Huhnke RL, Storm DE, Johnson GV, et al. Influence of buffers on pesticide and nutrient runoff from bermudagrass turf. J Environ Qual 1997;26:1589–98.

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

Correl DL. The role of phosphorus in the eutrophication of receiving waters — a review. J Environ Qual 1998;27:261–6.

Donn MJ, Barron OV, Barr AD. Identification of phosphorus export from low-runoff yielding areas using combined application of high frequency water quality data and MODHMS modeling. Sci Total Environ 2012;426:264–71.

Dunn JH, Minner DD, Fresenburg BF, Bughrara SS, Hohnstrater CH. Influence of core aerification, topdressing, and nitrogen on mat, roots and quality of 'Meyer' Zoysiagrass. Agron J 1995;87:891–4.

Ehigiator OA, Anyata BU. Effects of land clearing techniques and tillage systems on runoff and soil erosion in a tropical rain forest in Nigeria. J Environ Manag 2011;92:2875–80.

Franklin DH, Truman CC, Potter TL, Bosch DD, Stickland TC, Jenkins MB, et al. Nutrient losses in runoff from conventional and no-till pearl millet on pre-wetted Ultisols fertilized with broiler litter. Agric Water Manag 2012;113:38–44.

Gardner DS, Branham BE, Lickfeldt DW. Effect of turfgrass on soil mobility and dissipation of cyproconazole. Crop Sci 2000;40:1333–9.

Gross CM, Angle JS, Welterlen MS. Nutrient and sediment losses from turfgrass. J Environ Qual 1990;19:663–8.

Guillette LJ, Edwards TM. Is nitrate an ecological relevant endocrine disruptor in vertebrates? Integr Comp Biol 2005;45:19–27.

Hamilton GW, Waddington DV. Infiltration rates on residential lawns in central Pennsylvania. J Soil Water Conserv Soc 1999;54:564–8.

Hansen NC, Moncrief JF, Gupta SC, Capel PD, Olness AE. Herbicide banding and tillage system interactions on runoff losses of alachlor and cyanazine. J Environ Qual 2001;30:2120–6.

Harden CP. Incorporating roads and footpaths in watershed-scale hydrologic and soil-erosion models. Phys Geogr 1992;13:368–85.

Harris JR. Maintenance of soil structure under playing turf. In: Emerson WW, editor. Modifications of soil structure. Chichester, England: John Wiley & Sons; 1978.

Huff FA, Angel JR. Rainfall frequency atlas of the Midwest. MCC Research Report 92-03Bulletin, 71. Champaign, Illinois: Midwest Climate Center and Illinois State Water Survey; 1992 [http://wwwiswsillinoisedu/pubdoc/B/ISWSB-71pdf, last accessed September 20, 2012].

Jensen M. Runoff pattern and peak flows from moving block rains based on a linear time-area curve. Nord Hydrol 1984;15:155–68.

Kauffman GL, Watschke TL. Phosphorus and sediment in runoff after core cultivation of creeping bentgrass and perennial ryegrass turfs. Agron J 2007;99:141–7.

King KW, Harmel RD, Torbert HA, Balogh JC. Impact of a turfgrass system on nutrient loading to surface water. J Am Water Resour Assoc 2001;37:629–40.

Knobeloch L, Salna B, Hogan A, Postle J, Anderson H. Blue babies and nitrate-contaminated well water. Environ Health Perspect 2000;108:675–8.

Lake Scientist. Harmful Algal Blooms. http://wwwlakescientistcom/learn-about-lakes/water-quality/harmful-algal-bloomshtml2012. [last accessed September 20, 2012].

Linde DT, Watschke TL, Jarrett AR, Borger JA. Surface runoff assessment from creeping bentgrass and perennial ryegrass turf. Agron J 1995;87:176–82.

Lyman G, Throssell C, Johnson M, Stacey G, Brown C. Golf course profile describes turfgrass, landscape and environmental stewardship features. Appl Turfgrass Sci 2007. http://dx.doi.org/10.1094/ATS-2007-1107-01-RS.

Maetens W, Poesen J, Vanmaercke M. How effective are soil conservation techniques in reducing plot runoff and soil loss in Europe and the Mediterranean? Earth Sci Rev 2012;115:21–36.

McCarty LB, Gregg MF, Toler JE. Thatch and mat management in an established creeping bentgrass golf green. Agron J 2007;99:1530–7.

MPCA. Developing surface water nitrate standards and strategies for reducing nitrogen loading, wq-s6-23. Saint Paul, MN: Minnesota Pollution Control Agency; 2010 [2 pp. Available from: http://www.pca.state.mn.us/index.php/view-document.html?gid=15398].

Milesi C, Running SW, Elvidge CD, Dietz JB, Tuttle BT, Nemani RR. Mapping and modeling the biogeochemical cycling of turf grasses in the United States. Environ Manag 2005;36:426–38.

Miller RW. The thatch problem. Weeds Trees Turf 1965;4:10–8.

Monson P. Aquatic life water quality standards technical support document for nitrate, triennial water quality standard amendments to Minn. R. chs. 7050 and 7052, Draft for external review, wq-s6-13. Minnesota Pollution Control Agency; 2010 [Available from: http://www.pca.state.mn.us/index.php/view-document.html?gid=14949].

Murphy J, Riley JP. A modified single solution method for determination of phosphate in natural waters. Anal Chim Acta 1962;27:31–6.

Murphy JA, Rieke PE, Erickson AE. Core cultivation of a putting green with hollow and solid tines. Agron J 1992;85:1–9.

Murray JJ, Juska FV. Effects of management practices on thatch accumulation, turf quality, and leaf spot damage in common Kentucky bluegrass. Agron J 1977;69:365–9.

Nash D, Clemow L, Hannah M, Barlow K, Gangaiya P. Modeling phosphorus exports from rain-fed and irrigated pastures in southern Australia. Aust J Soil Res 2005;43:745–55.

Pärn J, Pinay G, Mander Ü. Indicators of nutrient transport from agricultural catchments under temperate climate: a review. Ecol Indic 2012;22:4-15.

Petrovic A. Dissertation abstract, ADG80-06178, Michigan State University Lansing, MI, URL http://guideslibmsuedu/pagephtml?page_id=1312, 1979.

Potter TL, Truman CC, Bosch DD, Bednarz C. Flumeturon and pendimethalin runoff from strip and conventionally tilled cotton in the southern Atlantic Coastal Plain. J Environ Qual 2004;33:2122–31.

Rice PJ, Horgan BP. Nutrient loss with runoff from fairway turf: an evaluation of core cultivation practices and their environmental impact. Environ Toxicol Chem 2011;30:2473–80.

Rice PJ, Harman-Fetcho JA, Sadeghi AM, McConnell LL, Coffman CB, Teasdale JR, et al. Reducing insecticide and fungicide loads in runoff from plastic mulch with vegetative-covered furrows. J Agric Food Chem 2007;55:1377–84.

Rice PJ, Horgan BP, Rittenhouse JL. Evaluation of core cultivation practices to reduce ecological risk of pesticides in runoff from *Agrostis palustris*. Environ Toxicol Chem 2010;9:1215–23.

Rice PJ, Horgan BP, Rittenhouse JL. 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, editors. Pesticide mitigation strategies for surface water quality. Washington DC: American Chemical Society Symposium Series; 2011. p. 95-113.

Rocha EO, Calijuri ML, Santiago AF, Campos de Assis L, Alves LGS. The contribution of conservation practices in reducing runoff, soil loss, and transport of nutrients at the watershed level. Water Resour Manage 2012;26:3831–52.

Rowland JH, Cisar JL, Snyder GH, Sartain JB, Wright AL. USGA ultradwarf Bermudagrass putting green properties as affected by cultural practices. Agron J 2009;101:1565–72.

Saito O. 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.

Sargent DM. An investigation into the effect of storm movement on the design of urban drainage systems: part I. Public Health Eng 1981;9:201–7.

Schindler DW. Evolution of phosphorus limitation in lakes. Science 1977;195:260–2.

Self-Davis ML, Moore PA, Joern BC. Determination of water- and/or dilute salt-extractable phosphorus. In: Pierzynski GM, editor. Methods of phosphorus analysis for soils sediments, residuals, and waters. Southern Cooperative Series BulletinNorth Carolina: North Carolina State University-Raleigh; 2000. p. 24–6.

Seo Y, Schmidt AR. The effect of rainstorm movement on urban drainage network runoff hydrographs. Hydrol Process 2012;26:3830–41.

Shuman LM. Phosphorus and nitrate nitrogen in runoff following fertilizer application to turfgrass. J Environ Qual 2002;31:1710–5.

Soulsby C, Rodgers PJ, Petry J, Hannah DM, Malcolm IA, Dunn SM. Using tracers to upscale flow path understanding in mesoscale mountainous catchments: two examples from Scotland. J Hydrol 2004;291:174–96.

Steel RGD, Torrie JH, Dickey DA. Principles and procedures of statistics: a biometrical approach. 3rd ed. New York: McGraw-Hill; 1997.

Stier JC, Hollman AB. Cultivation and topdressing requirements for thatch management in A and G bentgrass and creeping bluegrass. Hortic Sci 2003;38:1227–31.

Thomaz EL, Vestena LR. Measurement of runoff and soil loss from two differently sized plots in a subtropical environment (Brazil). Earth Surf Proc Land 2012;37:363–73.

Torisello J. Promote growth (Turfgrass maintenance). Golf Course Industry. August 21. Available from http://www.golfcourseindustry.com/Article.aspx?article_id=714882007.

Turgeon AJ. Turfgrass management. 2nd ed. Reston, Virginia: Reston Publishing; 1985.

United States Environmental Protection Agency. Quality criteria for water EPA 440/5-86-001. Washington DC: Office of Water Regulations and Standards; 1986.

Vadas PA, Owens LB, Sharpley AN. An empirical model for dissolved phosphorus in runoff from surface-applied fertilizers. Agric Ecosyst Environ 2008;127:59–65.

Van Liew MW, Green CH, Starks PJ. Unit source area data: can it make a difference in calibrating the hydrologic response for watershed-scale modeling? J Soil Water Conserv 2007;62:162–70.

Vargas JM, Turgeon AJ. *Poa annua*: physiology, culture, and control of annual bluegrass. Hoboken, New Jersey: John Wiley & Sons; 2004.

Waltz C. BMPs for turfgrass water conservation in landscapes. University of Georgia Cooperative Extension Bulletin, 1329; 2007 [September 42 pp., Available from: http://apps.caes.uga.edu/urbanag/pubs/bmp_watercon.pdf.].

Watson JR, Kaerwer HE, Martin DP. The turfgrass industry. In: Waddington DV, editor. Turfgrass, 32. Agronomy Monograph; 1992. p. 29–88. [Madison, Wisconsin].

Wauchope RD, Williams RG, Marti LR. Runoff of sulfometuron-methyl and cyanazine from small plots: effects of formulation and grass cover. J Environ Qual 1990;19:119–25.

White RH, Dickens R. Thatch accumulation in bermudagrass as influenced by cultural practices. Agron J 1984;76:19–22.

Xu L, Zhang Q, Li H, Viney NR, Xu J, Liu J. Modeling of surface runoff in Xitiaoxi catchment, China. Water Resour Manage 2007;21:1313–23.

Yen BC, Chow VT. A laboratory study of surface runoff due to moving rainstorms. Water Resour Res 1969;5:989-1006.