The Fate and Transport of Phosphorus in Turfgrass Ecosystems

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ABSTRACT

Phosphorus losses from turfgrass areas are perceived to contribute to water quality problems, yet a comprehensive review of P fate in turfgrass ecosystems is lacking. According to available data in the literature, phosphorus fertilizer inputs (2–10 kg ha^{-1}) slightly exceed the estimated outputs of phosphorus in clippings (0.4–7.5 kg ha^{-1}). Sediment losses from turf areas are negligible, generally limited to establishment, but runoff and leaching losses of P vary from inconsequential to severe depending on rate, source, and timing of fertilizer application. Soil properties were found to have a larger effect on runoff volume than vegetative properties. Highest runoff and leaching losses of P occurred when rainfall occurred or was simulated shortly after P fertilizer application. Leaching losses of P have historically been considered relatively minor; however, the limited research results available indicate that annual P leaching losses from mineral soils (0.2–0.7 kg ha^{-1}) are similar in magnitude to runoff-P losses from turfgrass systems. One major gap in the knowledge is how P sources other than fertilizer (i.e., soil and plant tissue) and irrigation affect runoff and leaching losses of P.

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Abbreviations: BMPs, best management practices; DP, dissolved phosphorus; MRP, molybdate reactive phosphorus; TDP, total dissolved phosphorus; TP, total phosphorus; TSS, total suspended solids.

Poor water quality is a widespread problem for many of the surface water bodies in the U.S. Excessive nutrient levels are responsible for water quality impairment in 20% of rivers and streams and 50% of lakes and reservoirs (USEPA, 2002). There is considerable evidence that P is the limiting nutrient for unwanted algal growth in most fresh surface-water bodies (Correll, 1998) and excessive P inputs will often result in a decline in surface water quality. Phosphorus can enter a water body through point sources, such as sewage or industrial outfalls, or through nonpoint sources, which arise from spatially and temporally variable areas of the landscape. Nonpoint sources typically include crop management systems and other land uses where P-containing materials are applied. Agricultural and urban areas are cited as the two most important contributors to nonpoint-source pollution (Carpenter et al., 1998).

In the last few decades a significant amount of research has been conducted on agricultural losses of P as summarized by Sims and Sharpley (2005). The results of such research have led to the development of risk assessment tools and management strategies for reducing P loss from agricultural land. However, far less work has been conducted on P losses from urban and suburban areas, despite the fact that these areas are growing at a rate of 567,000 ha yr^{-1}

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(Heimlich and Anderson, 2001). Turfgrass is the dominant component of pervious areas in urban and suburban landscapes (Milesi et al., 2005) and is highly managed in some settings. Because of the growing importance of P loss from turfgrass areas, we felt a review and synthesis of the current body of literature related to turfgrass-P losses was needed to assess the variability of P losses from a range of turfgrass ecosystems, and identify relevant knowledge gaps that can guide future P-related turfgrass research.

PHOSPHORUS CYCLE IN TURFGRASS ECOSYSTEMS

Phosphorus Inputs

The primary P input to turfgrass systems is surface-applied organic or inorganic fertilizers. Homeowners and other non-professional turfgrass managers usually apply fertilizer to meet N requirements, and therefore, the amount of P applied is dependent on the fertilizer's N:P ratio. Following the fertilizer label directions of various so-called "four step programs" will result in the application of 16 to 73 kg P_2O_5 ha^{-1} yr^{-1} (7–32 kg P ha^{-1} yr^{-1}), depending on the product or manufacturer. The leading commercial four-step program results in the application of 7 kg P ha^{-1} yr^{-1}. Organic fertilizers typically have greater N:P ratios than inorganic fertilizers and will result in 39 to 122 kg P_2O_5 ha^{-1} yr^{-1} (17–54 kg P ha^{-1} yr^{-1}) when fertilizer is applied at the manufacturer's typically recommended annual rate of 195 kg N ha^{-1} yr^{-1}.

The actual amount of P fertilizer applied to turfgrass is fairly difficult to know with much accuracy on a large scale, but generalizations can be made using surveys, fertilizer sales data, and information on turfgrass area in the landscape. A recent survey of the turfgrass management practices in five communities in North Carolina revealed that 54 to 83% (varied by community) of homeowners apply fertilizer at least once per year (Osmond and Hardy, 2004). This finding was corroborated by a Georgia survey that found 76% of homeowners apply fertilizer to their lawns, although the amount of fertilizer could not be determined (Varlamoff et al., 2001). Annual N application rates for the North Carolinian homeowners applying fertilizer ranged from 24 to 151 kg N ha^{-1} yr^{-1}, suggesting that P applied by homeowners is significantly lower than the amounts recommended by fertilizer manufacturers (150–200 kg N ha^{-1}). Data compiled by The Scotts Company reports that 56% of the 90 million homeowners in the U.S. apply lawn fertilizer (Augustin, 2007). Of the fertilized lawns, the average number of annual fertilizer applications was reported to be 1.8, which includes an estimated 10 million lawns serviced by a professional lawn-care company (five fertilizer applications per year were assumed for this group). The preceding information suggests that the average number of annual fertilizer applications for all home lawns in the US is 1.1. Using the data on actual homeowner fertilization practices and the range in P_2O_5 content for inorganic commercial lawn fertilizers listed in the previous paragraph, P fertilizer inputs to a suburban ecosystem are probably between 4 to 22 kg P_2O_5 ha^{-1} yr^{-1} (2–10 kg P ha^{-1} yr^{-1}). If the leading manufacturer's product is assumed for all applications, then the national P input to lawns is 2 kg P ha^{-1} yr^{-1}. However, this estimate is considerably lower than that found by a recent survey to assess watershed-scale N inputs from lawn fertilization in Baltimore County, MD (Law et al., 2004). The authors estimated mean N inputs to fertilized lawns to be 96 kg ha^{-1} yr^{-1}. If an N:P ratio of 10:1 is assumed for the fertilizer applied, then the phosphorus application was 9.6 kg P ha^{-1} yr^{-1}. In that study, 32 to 44% of respondents did not fertilize, resulting in an average P input of 5.4 to 6.5 kg P ha^{-1} yr^{-1} to residential lawns.

Another secondary, but potentially important P input is atmospheric deposition. Annual wet atmospheric deposition inputs of P (from precipitation) for a small watershed in Upstate New York were 0.15 kg ha^{-1} (Easton and Petrovic, 2008); and wet and dry atmospheric deposition inputs amounted to 0.77 kg ha^{-1} yr^{-1} for the Upper Potomac River Basin (Jaworski et al., 1992). Dry deposition of phosphorus occurs from accumulation of solids such as dust and other aerosols (Carbo et al., 2005).

Phosphorus Outputs

Clipping Removal of Phosphorus

When P is not the growth limiting nutrient, the amount of P removed by clippings is dependent on the growth rate of the turfgrass, which is influenced by species, temperature, available moisture, and N application rate. Turfgrass tissue typically contains 2.0 to 5.0 g P kg^{-1} of dry matter (Guillard and Dest, 2003; Johnson et al., 2003; Miller and Thomas, 1999). Kopp and Guillard (2002) found average clipping production of mixed stands of cool-season grasses from two sites in Connecticut to be 1000 to 3000 kg ha^{-1} (depending on N fertilization rate) when clippings were removed. Therefore, in temperate climates, removing clippings could result in the removal of 2 to 15 kg P ha^{-1} yr^{-1}. Supporting this calculation, Easton and Petrovic (2004) reported P annual clipping removal of a mixed stand of *P. pratensis* and *Lolium perenne* L. in New York to be 4 to 13 kg ha^{-1} dependent on fertilizer rate and source. If clippings were removed from all lawns, it appears that outputs might exceed inputs. Very little information exists regarding the percentage of homeowners who actually remove clippings from their lawns. Osmond and Hardy (2004) found 50% of homeowners in five communities in North Carolina collected and removed grass clippings from their lawns compared to 20% in Edina, MN (Carpenter and Meyer, 1999). Therefore, based on the rudimentary data available, the primary inputs of fertilizer

(2–10 kg P ha^{-1} yr^{-1}) appears to be slightly greater than the estimated outputs of clippings (0.4–7.5 kg P ha^{-1} yr^{-1}). If these data are reliable, soil P levels would be expected to remain constant or increase slightly over a number of years. However, very limited information about the historical trends in soil P levels for turfgrass areas is available. Bennett et al. (2004) randomly sampled soils from cash grain, dairy farm, prairie, and lawn soils in the Madison, WI area. They found that home lawns had greater soil P levels compared to prairie, but were lower than those of the surrounding cash grain and dairy farm soils from which the lawn soils were likely derived as the suburbs encroached on agricultural land. Historical analysis of soil samples submitted to soil testing laboratories would be beneficial to validate the above predictions of P levels in lawns and turfgrass areas.

Sediment Losses from Turfgrass Systems

Dense stands of grass have long been known to be effective at reducing soil erosion. In 1935 Hugh H. Bennett, regarded by the National Resource Conservation Service (NRCS) as the father of soil conservation, wrote: "The importance of grass as a means of controlling erosion is so great that this paper may appropriately be prefaced with the assertion that where there is a good cover of grass there is no serious problem of erosion." (Bennett, 1935). Today, grass buffer strips and vegetated waterways are two commonly employed best management practices (BMPs) for minimizing sediment loss from agricultural areas (Sims and Kleinman, 2005). The effectiveness of grassed waterways and vegetated buffers at reducing sediment and P loss is highly variable and found to depend on such factors as runoff volume input and physical characteristics of the site (soil, slope) and grass waterway or buffer strip (width, grass type, density, management). Vegetated filter strips and waterways function primarily to reduce erosion and particulate P loads, but also have been shown to decrease soluble P load in runoff by reducing runoff volume (Abu-Zreig et al., 2003; Fiener and Auerswald, 2003).

Turfgrass forms a dense ground cover with shoot density ranging from 7500 to 2 million shoots m^{-2} (Beard and Green, 1994), depending on turfgrass species and management. Consequently, sediment loss from turfgrass areas has been found to be very low (Table 1). Linde and Watschke (1997) found no detectable sediment in 83% of 237 runoff samples from creeping bentgrass and perennial ryegrass turf. Sediment losses from natural rainfall events on cool-season turfgrass species ranged from undetectable (Kussow, 2008), to very low (3.2–16.2 kg ha^{-1}; Gross et al., 1990). Gross et al. (1991) used simulated rainfall to generate sediment losses from bare soil and low-density turfgrass. They found that even at low turf density (57 tillers dm^{-1}), sediment loss were reduced by an order of magnitude compared to sediment losses from bare soil (Table 1). Similarly, Krenitsky et al. (1998) found turfgrass sod to be an extremely effective erosion control material for construction sites, with sediment reductions of 99% compared to bare soil. Sediment losses from turfgrass and a prairie mixture of legumes, grasses, and forbs were compared by Steinke et al. (2007). The authors found sediment losses from turfgrass to be 1.9 kg ha^{-1} yr^{-1} during the growing season, and 231 kg ha^{-1} yr^{-1} during runoff when soil was frozen. Sediment losses from the prairie were 13.2 kg ha^{-1} yr^{-1} during the growing season and 210 kg ha^{-1} yr^{-1} when soil was frozen.

Sediment losses from turfgrass have also been measured on a watershed scale. Researchers in Kansas monitored stream water quality of a native grassland watershed before, during, and after the conversion of a prairie to an 18-hole golf course (Starrett et al., 2006). In-stream total suspended solids (TSS) before construction were 477 mg L^{-1}. During construction, TSS increased to 2754 mg L^{-1}, and dropped to 550 mg L^{-1}, a 15% increase from the preconstruction level, during the early stages of golf course operation. Stream discharge was not monitored; changes in discharge would likely affect sediment loading. Total suspended solids in 24 tributaries to the Mississippi River near St. Paul, MN ranged from 2 to 768 kg ha^{-1} yr^{-1} (mean of 218 kg ha^{-1} yr^{-1}, Kloiber, 2006).

Sediment losses from managed grassland systems are typically greater than those from turfgrass areas. A review reported sediment losses of 130 to 2231 kg ha^{-1} yr^{-1} from New Zealand pastures (Gillingham and Thorrold, 2000). Smith et al. (1992) reported sediment losses ranging from 29 to 25,019 kg ha^{-1} yr^{-1} from several grasslands in Oklahoma of varying land use and condition.

Runoff Losses in Turfgrass Systems

Runoff research on turfgrass can be sorted into three general categories (i) plot-scale, worst-case scenario research where runoff is simulated on small plots shortly after a fertilizer application is made, (ii) plot-scale research where runoff is collected from natural precipitation or rainfall events, and (iii) watershed-scale research where runoff losses from turfgrass areas are estimated by changes in flow and P concentration of a water body flowing through a turfgrass-dominated landscape.

The studies documenting P runoff losses from turfgrass are summarized in Table 2. In general, P runoff losses from simulated rain events on recently fertilized turfgrass areas (worst-case scenario) have been shown to vary with rate of P application, with greater losses occurring from higher rates of P application. A portion of the P in runoff can be easily traced back to fertilizer when unfertilized control plots are included in the study. Losses of P from these types of studies have ranged from <1 to 18% of fertilizer P applied, with single-event P loads from 0.04 to 3.1 kg ha^{-1} (Table 2).

Table 1. Sediment losses in runoff from turfgrass for both natural and simulated rain events.

Ground cover	Turf density	Soil type	Slope	Runoff generation process and study scale	Sediment loss	Reference
	tillers dm^{-2}		%		kg ha^{-1}	
Festuca arundinacea Schreb./*P. pratensis*	NR	Westphalia fine sandy loam (Typic Hapludult)	5-7	Natural plot-scale 295 mm yr^{-1}, over 2 yr	3.2–16.2 yr^{-1}	Gross et al., 1990
F. arundinacea	0	Westphalia fine sandy loam (Typic Hapludult)	8	Simulated plot-scale 76 mm h^{-1}, 0.5 h	44.4 event^{-1}	Gross et al., 1991
	21			76 mm h^{-1}, 0.5 h	12.0 event^{-1}	
	57			76 mm h^{-1}, 0.5 h	4.8 event^{-1}	
	0			94 mm h^{-1}, 0.5 h	68.4 event^{-1}	
	21			94 mm h^{-1}, 0.5 h	15.0 event^{-1}	
	57			94 mm h^{-1}, 0.5 h	6.6 event^{-1}	
	0			120 mm h^{-1}, 0.5 h	103.8 event^{-1}	
	21			120 mm h^{-1}, 0.5 h	21.0 event^{-1}	
	57			120 mm h^{-1}, 0.5 h	10.8 event^{-1}	
Poa pratensis L.	NR†	Troxel silt loam (Pachic Agriudoll)	6	Natural plot-scale 780 mm yr^{-1}, over 6 yr	0.0 yr^{-1}	Kussow, 2008
Sprigged Cynodon dactylon	NR	Booneville fine sandy loam (Pachic Agricryoll)		Natural plot-scale 247 mm^{-1} fall 2000 98 mm^{-1} spring 2001	104–146 yr^{-1}	Vietor et al., 2004
Sodded C. dactylon	NR				38.4–117 yr^{-1}	
Established C. dactylon	NR				68 yr^{-1}	
A. paulustris	NR	Hagerstown clay (Typic Hapludulf)	9–11	Simulated plot-scale 152 mm h^{-1}, 0.25 h^{-1}	0.10–0.19 event^{-1}	Kauffman and Watschke, 2007
L. perenne	NR			Simulated plot-scale 152 mm h^{-1}, 0.20 h^{-1}	0.15–0.33 event^{-1}	
P. pratensis	2% bare soil	Batavia silt loam (Fluvaquentic Endoaquoll) *FROZEN*	6	Natural plot-scale 817.4 mm yr^{-1}, over 2 yr with approx. 80% of runoff occurring during frozen soil conditions	231 yr^{-1}	Steinke et al., 2007
	2% bare soil	Batavia silt loam (Fluvaquentic Endoaquoll) *NON-FROZEN*	6		1.9 yr^{-1}	
Prairie mixture of legumes, grasses and forbs	36% bare soil	Batavia silt loam (Fluvaquentic Endoaquoll) *FROZEN*	6		210 yr^{-1}	
	36% bare soil	Batavia silt loam (Fluvaquentic Endoaquoll) *NON-FROZEN*	6		13.2 yr^{-1}	

†NR; not reported.

Phosphorus runoff losses from natural events at the plot-scale are expectedly lower than those of the worst-case scenario group. In natural, plot-scale studies, annual P loads ranged from 0.26 to 2.1 kg ha^{-1} yr^{-1} (Table 2), similar in magnitude to single-event worst-case scenario events. It is informative that a single intense runoff event immediately following a fertilizer application could account for a "normal" year's worth of P loss from a site.

In some cases, P runoff losses from unfertilized (no N or P) turfgrass areas have been found to be greater than P losses from fertilized turfgrass (Table 2). The watershed-scale studies reported annual P losses from golf courses of 0.02 to 2.05 kg ha^{-1}. The study that found the highest P loss (2.05 kg ha^{-1}, Kunimatsu et al., 1999) failed to quantify the P exported by a wastewater treatment plant operating within the golf course watershed. Excluding that study, the watershed exports of P have been found to be at or below 0.51 kg ha^{-1} yr^{-1}; generally lower than annual P export estimates from natural event plot-scale research, which suggest these studies tend to overestimate runoff P losses from turfgrass areas. Carroll et al. (2007) found that large runoff plots (465 m^2) have greater total P (TP) losses than small plots (118 m^2); however, the runoff processes at the plot-scale are likely different that those working at the watershed scale.

Phosphorus runoff load to a water body is the product of P concentration in runoff and runoff volume. Therefore, P loads can be reduced by reducing either P concentration or runoff volume. Researchers have studied the mechanisms of runoff volume reduction in turfgrass systems. Gross et al. (1990) seeded tall fescue (*Festuca arundinacea* Schreb.) at different rates into a sandy loam soil to achieve a range in turfgrass shoot density. Simulated rainfall was applied to force runoff from the plots. No differences in runoff volume were detected for shoot densities ranging from 867 to 5692 tillers m^{-2}, a range on the low end of commonly observed turfgrass densities. In contrast, Easton et al. (2005) found that infiltration increased from 7 to 21 cm h^{-1} as turfgrass shoot density increased from 60,000 to 120,000 shoots m^{-2}. In their study, fertilized

Table 2. Runoff losses of P from turfgrass systems.

Ground cover	Soil type	Slope	Runoff generation process and study scale	P source (N-P-K)	P application rate	P load	P conc. in runoff	Loss of applied P†	Reference (form‡ of P measured)
		%			kg ha^{-1}	kg ha^{-1}	mg L^{-1}	%	
Cool season lawns in Wisconsin	Heavily disturbed silt loam	4–8	Simulated plot-scale 120 mm h^{-1}, 1.5 h	NR¶ (10–4.4–8.3)	0 43 99	0.9 event^{-1} 4.0 event^{-1} 12.4 event^{-1}	0.4 0.5 8.4	7.2 11.6	Kelling and Peterson, 1975 (DRP)
	Undisturbed silt loam over sandy loam	4–8	Simulated plot-scale 120 mm h^{-1}, 1.5 h	NR (10–4.4–8.3)	0 21 43	0.05 event^{-1} 0.5 event^{-1} 0.2 event^{-1}	0.05 0.5 0.1	2.1 0.3	
F. arundinacea + *P. pratensis*	Westphalia fine sandy loam (Typic Hapludult)	5–7	Natural plot-scale 295 mm yr^{-1}, over 2 yr	N/A§	0	0.01–0.04	NR	N/A	Gross et al., 1990 (TP)
Cynodon. dactylon L.	Kirkland silt loam (Udertic Paleustoll)	6	Simulated plot-scale 51–64 mm h^{-1}, 1.3–2.3 h With buffer (2.4–4.9 m)	Superphosphate (0–8.8–0)	49	0.04–0.53 event^{-1}	0.78–2.36	Less than control– 1.0	Cole et al., 1997 (DRP)
		6	Simulated plot-scale 51–64 mm h^{-1}, 1.3–2.3 h Without buffer (2.4–4.9 m)	Superphosphate (0–8.8–0)	49	1.03 event^{-1}	9.57	2.0	
		6	Simulated plot-scale 51–64 mm h^{-1}, 1.3–2.3 h Without buffer (2.4– 4.9 m)	N/A	0.0	0.06 event^{-1}	0.42	N/A	
L. perenne or *A. stolonifera* var. *palustris*	Hagerstown clay, depth to bedrock 5– 60 cm (Typic Hapludulf)	9- 11	Natural plot-scale 210 mm yr^{-1}, over 2 yr	MAP# (19–1.3–15)	6 (year 1) 11 (year 2)	0.0– 0.2 yr^{-1}	1.6–6.6	No control	Linde and Watschke, 1997 (MRP)
			Simulated plot-scale 139 mm h^{-1}, 0.25– 0.42 h^{-1}	MAP (19–1.3–15)	6 (year 1) 11 (year 2)	0.0–0.6 event^{-1}	NR	No control	
Chamaecyparis obtuse (Japanese Cyprus)	NR	NR	Natural watershed-scale 1947 mm^{-1} in 1989 2054 mm^{-1} in 1990	Unfertilized	0	0.049 yr^{-1}	0.004	N/A	Kunimatsu et al., 1999 (DRP)
Zoyzia matrella MERR.	NR	NR		NR	21	2.05 yr^{-1}	0.081	N/A	
C. dactylon and *L. perenne*	Several, primarily gravelly loamy sand and silty clay loam	N/A	Natural watershed-scale 738 mm 13 mo. $^{-1}$	738 mm 13 mo. $^{-1}$	50 kg ha^{-1} over 13 mo	0.33 yr^{-1}	0.10–0.13	No control	King et al., 2001 (MRP)
C. dactylon	Boonville fine sandy loam (Vertic Albaqualf)	8.5	Natural plot-scale 143 mm yr^{-1}, over 2 yr	N/A	0	4.6 yr^{-1}	1.1–2.6		Gaudreau et al., 2002 (TDP)
				Inorganic P	25 50	8.0 yr^{-1} 11.8 yr^{-1}	1.1–16.6 1.1–30.0	13.6 14.4	
				Dairy manure	50 100	7.7 yr^{-1} 11.7 yr^{-1}	2.4– 5.5 2.8– 9.8	6.2 7.1	
C. dactylon	Cecil sandy loam (Typic Kanhapludult)	5	Simulated plot-scale 27 mm h^{-1}, 2 h 4, 24 HAT††	N/A	0 4 HAT 24 HAT 72 HAT 168 HAT	 0.12 event^{-1} 0.09 event^{-1} 0.04 event^{-1} 0.04 event^{-1}	 1.0 0.5 1.1 1.0	N/A	Shuman, 2002 (DRP)
				MAP (10–4.4–8.3)	5 4 HAT 24 HAT 72 HAT 168 HAT	 0.66 event^{-1} 0.20 event^{-1} 0.08 event^{-1} 0.05 event^{-1}	 4.0 1.1 0.8 1.0	 10.9 3.8 0.8 0.2	
				MAP (10–4.4–8.3)	11 4 HAT 24 HAT 72 HAT 168 HAT	 1.19 event^{-1} 0.44 event^{-1} 0.12 event^{-1} 0.06 event^{-1}	 7.0 1.8 1.2 0.8	 9.7 3.2 0.7 0.2	

Table 2. Continued.

Ground Cover	Soil type	Slope	Runoff generation process and study scale	P source	P application rate	P load	P conc. in runoff	Loss of applied P	Reference (form of P measured)
		%			kg ha^{-1}	kg ha^{-1}	mg L^{-1}	%	
P. pratensis + *L. perenne*	Arkport sandy loam (Lamellic Hapludalf)	7-9	Natural plot-scale 268 mm yr^{-1}, over 2 yr	N/A	0.0	0.8 yr^{-1}	0.4	N/A	Easton and Petrovic, 2004 (MRP)
				Swine compost (4.25–0.9–0)	42	1.1 yr^{-1}	1.2	0.3	
				Dairy compost (0.8-.13–0)	33	0.6 yr^{-1}	0.8	Less than control	
				Biosolids (6–0.9–0)	29	0.6 yr^{-1}	0.6	Less than control	
				MAP (35–1.3–4)	7.5	0.4 yr^{-1}	0.4	Less than control	
				MAP (24–2.2–9)	18	0.6 yr^{-1}	0.4	Less than control	
C. dactylon sprigged and sodded	Booneville fine sandy loam (Pachic Agricryoll)	8.5	Natural plot-scale 247 mm^{-1} fall 2000 98 mm^{-1} spring 2001	Sprigged plots topdressed with composted dairy manure	184 92	19.1 yr^{-1} 15.0 yr^{-1}	3.4–11.9 2.3–10.7	8.2 11.8	Vietor et al., 2004 (TDP)
				Sprigged plots topdressed with TSP‡‡	100	10.6 yr^{-1}	0.9–20.5	6.5	
				Sodded with grass grown on dairy manure	392 191	10.8 yr^{-1} 6.5 yr^{-1}	4.9–14.9 2.1–8.5	1.7 1.3	
				Sodded with inorganically fertilized	70	7.2 yr^{-1}	0.5–9.6	4.4	
				Established control	0	4.1 yr^{-1}	0.5–5.5	N/A	
Cool season lawn turf in New York	Silt loam	7-11	Natural plot-scale 1268 mm yr^{-1}, over 2 yr	N/A	0	0.57 yr^{-1}	0.10–1.30	N/A	Easton and Petrovic, 2008 (MRP)
Cool season lawn turf in New York	Silt loam	7–11		MAP	28 yr^{-1}	0.51 yr^{-1}	0.98–1.36	Less than control	
Wooded land in suburban New York	Silt loam	7–11		N/A	0	0.42 yr^{-1}	0.15– 0.48	N/A	

plots had greater shoot densities and thus exhibited lower runoff volumes and P losses than unfertilized control plots. In addition to density differences due to fertilization or seeding rates, turfgrass species have inherent differences in shoot density. Linde et al. (1995) observed that creeping bentgrass reduced runoff losses when compared with perennial ryegrass when both grasses were mown at 19 mm. The authors attributed the reduction in runoff volume from creeping bentgrass to its greater shoot density which allowed for increased water infiltration. However, a follow-up study found no differences in runoff volume when soil moisture differences between the two species were controlled (Linde and Watschke, 1997). This suggests that differences in water use and water management among turfgrass species may be more important than differences in density. Indeed, other researchers have found soil moisture content to be highly correlated with runoff volume from turfgrass areas (Shuman, 2002; Easton and Petrovic 2004). However, to our knowledge no studies have been conducted that quantify the potential differences in runoff losses from irrigated and nonirrigated turfs (assuming equal natural precipitation).

In addition to the effects of density and soil moisture on runoff volumes, researchers have determined that increasing mowing height of grasses can decrease runoff losses from turfgrass areas (Cole et al., 1997; Moss et al., 2006), despite the fact that increased mowing height is normally associated with decreased turfgrass shoot density (Madison, 1962). This suggests that mowing height has a greater influence on runoff volumes than shoot density, whether this is the result of a reduction in soil moisture (due to greater evapotranspiration) or an increase in resistance to flow (or both) has not been documented. The assumption that increased mowing height leads to lower runoff volumes is incorporated into the NRCS Curve Number runoff estimation model for turfgrass (Haith,

Table 2. Continued.

Ground Cover	Soil type	Slope	Runoff generation process and study scale	P source	P application rate	P load	P conc. in runoff	Loss of applied P	Reference (form of P measured)
		%			kg ha^{-1}	kg ha^{-1}	mg L^{-1}	%	
Cool season golf turf in Ontario	Dominantly podzolic or brunisolic	N/A	Natural watershed-scale, Precipitation not reported	Primarily MAP and organic	5–10 yr^{-1}	0.02–0.08 yr^{-1} mean 0.03	0.07–0.23 mean 0.13	No control	Winter and Dillon, 2006 (TP)
A. paulustris	Hagerstown clay (Typic Hapludulf)	9–11	Simulated plot-scale 152 mm h^{-1}, 0.25 h^{-1}	DAP + aerification	42	0.025–0.065 event^{-1}	0.27–5.13	N/A	Kauffman and Watschke, 2007 (MRP)
L. perenne			Simulated plot-scale 152 mm h^{-1}, 0.20 h^{-1}	DAP + aerification	42	0.08–0.105 event^{-1}	0.30–4.21	N/A	
C. dactylon and *L. perenne*	Several, primarily gravelly loamy sand and silty clay loam	N/A	Natural watershed-scale 631 mm^{-1} Apr–Dec 1998, 510 mm^{-1} in 1999, 877 mm^{-1} in 2000, 965 mm^{-1} in 2001 692 mm^{-1} in 2002 154 mm^{-1} Jan– Mar 2003	Several	8.2 yr^{-1}	0.51 yr^{-1}	Inflow median = 0.10 Outflow median = 0.13	No control	King et al., 2007 (DRP)
C. dactylon	Norge silt laom (Udic Paleustoll)	5	Simulated plot-scale 51 mm h^{-1}, 0.12 h	Unfertilized with aerification Unfertilized without aerification	0 0	0.028 event^{-1} 0.023 event^{-1}	1.2–1.5 1.0–1.8	N/A	Moss et al., 2007 (DRP)
P. pratensis	Batavia silt loam (Fluvaquentic Endoaquoll) *FROZEN*	6	Natural plot-scale 817.4 mm yr^{-1}, over 2 yr with approx. 80% of runoff occurring during frozen soil conditions	MAP (21–1.3–10)	9.2 yr^{-1}	2.11 yr^{-1}	NR	No control	Steinke et al., 2007 (TP)
	Batavia silt loam *NON-FROZEN*	6		MAP (21–1.3–10)	9.2 yr^{-1}	0.01 yr^{-1}	NR	No control	
Prairie mixture of legumes, grasses and forbs	Batavia silt loam *FROZEN*	6		N/A	0	1.92 yr^{-1} (DP)	NR	N/A	
	Batavia silt loam *NON-FROZEN*	6		N/A	0	0.04 yr^{-1} (DP)	NR	N/A	
P. annua with no buffer strip	Silt to sandy loam	1–4	Natural plot-scale 908 mm in 2004 822 mm in 2005	N/A	0	0.08 yr^{-1} (TP)	0.33–0.58 (DP)	N/A	Stier and Kussow, 2006 (TP/DP)
P. annua with prairie buffer strip				N/A	0	0.09 yr^{-1} (TP)	0.13–0.56 (DP)	N/A	
P. annua with fescue buffer strip				N/A	0	0.11 yr^{-1} (TP)	0.07–0.49 (DP)	N/A	
A. palustris, P. annua and P. pratensis	Clayey, lacustrine, non-calcareous soils	N/A	Natural watershed-scale 353 mm^{-1} in 2003 482 mm^{-1} in 2004 533 mm^{-1} in 2005 418 mm^{-1} in 2006	Several	13.6 yr^{-1}	0.14 yr^{-1} (DRP) 0.24 yr^{-1} (TP)	Inflow median = 0.01 Outflow median = 0.015 (DP)	N/A	King and Balogh, 2008 (TP/DRP)
P. pratensis	Troxel silt loam (Pachic Agriudoll)	6	Natural plot-scale 798 mm yr^{-1}, over 2 yr	Biosolids (6–0.9–0)	0.6	0.37 yr^{-1}	NR	Less than control	Kussow, 2008 (MRP)
		6		Synthetic (29–1.3–3.5)	0.2	0.34 yr^{-1}	NR	Less than control	
		6		Unfertilized	0	0.54 yr^{-1}	NR	N/A	

†Loss of applied P calculated as P runoff load in fertilized plot– P runoff load in unfertilized plot)/P fertilizer applied, if no control was used applied P loss cannot be calculated.

‡DP, dissolved phosphorus; DRP, dissolved reactive phosphorus; MRP, molybdate reactive phosphorus; TP, total phosphorus.

¶NR, not reported.

§N/A; not applicable.

#MAP, monoammonium phosphate.

††HAT, hours after treatment.

‡‡TSP, triple super phosphate (0–46–0).

2001). In contrast, Stier and Kussow (2006) reported no differences in P runoff from fairway turf and runoff from fairway turf that was filtered through buffer strips of prairie species or unmanaged fescue.

Although it has been observed that turfgrass properties influence runoff volumes, a recent study demonstrated that runoff in a suburban watershed was as dependent on soil properties as ground cover (Easton and Petrovic, 2008). Runoff was collected from plots from (i) high maintenance, fertilized turfgrass, (ii) low maintenance, unfertilized turfgrass, and (iii) wooded areas. The plots were replicated throughout various areas of a 332 ha suburban watershed. High maintenance turfgrass reduced runoff volume by a factor of two compared to the low-maintenance and wooded areas. However, the variation in soil properties throughout the watershed had the largest effect on runoff volume. Runoff volume differences were up to an order of magnitude greater in areas with shallow, finer-textured soils than in areas with deeper, sandier soils. These differences were observed regardless of ground cover. Hamilton and Waddington (1999) found no significant correlations between infiltration rate and tiller density, soil bulk density, or soil texture for lawns in central Pennsylvania. They hypothesized that excavation procedures and establishment techniques influenced infiltration/runoff to a much greater extent than the turfgrass properties. Similarly, Kelling and Peterson (1975) found that lawns growing on soils heavily disturbed during home construction had infiltration rates of approximately one-third of non-disturbed sites. The authors concluded that P loss was determined more by the infiltration properties of the soil rather than the amount of applied fertilizer. Kussow (2008) also concluded that runoff volumes play the largest role in determining P runoff losses. It can be concluded that soil characteristics can have as much or a greater influence on runoff P losses than the type and condition of vegetative ground cover in turfgrass areas.

Similarly to the landscape-scale runoff processes, temporal runoff losses from turfgrass areas are poorly understood. Steinke et al. (2007) found over 80% of runoff from turfgrass and prairie vegetation occurred when soil was frozen in Wisconsin. Similarly, Kussow (2008) observed that runoff from snowmelt on Kentucky bluegrass lawn plots in the upper-Midwest accounted for 87% of total annual runoff over a six-year period. During the growing season, the author found increased runoff from turfgrass areas where the subsoil was compacted, but because the majority of the runoff occurred in the winter when soils were frozen the difference in annual runoff volume between compacted and uncompacted lawns was not significant. This suggests that BMPs related to snowmelt management should be a higher priority than BMPs related to construction practices in cold climates such as Wisconsin's.

The runoff P losses summarized in Table 2 are generally similar to or lower than those found in other systems. The 20th and 80th percentile for TP export from tributaries to the Mississippi River near St. Paul, MN from 2001 to 2003 were 0.28 and 0.95 kg ha^{-1} yr^{-1} (Kloiber, 2006), which were similar to those reported for Chesapeake Bay tributaries (0.39–0.90 kg ha^{-1} yr^{-1}) by Langland et al. (1998). These watersheds contain both urban and agricultural land uses, and the P losses reported are similar to those from plot-scale and watershed-scale turfgrass runoff studies (Table 2). Researchers found that golf courses in Texas (King et al., 2007) and Minnesota (King and Balogh, 2008) both contributed significantly to dissolved phosphorus (DP) in streams flowing into the courses from forested/low-density housing (MN) and urban land including an airport (TX). However, these losses have the potential to be reduced by altering the flow path of the stream within the golf course. Kohler et al. (2004) described the benefits of constructed wetlands on a golf course. They found wetlands reduce P export (along with 10 other water quality parameters), effectively cleaning the runoff from the golf course and upper contributing urban watershed.

Runoff P losses from turfgrass tend to be similar to those of pastures and grasslands. A review of New Zealand pastures reported TP losses of 0.11 to 1.6 kg ha^{-1} yr^{-1} (Gillingham and Thorrold, 2000). Smith et al. (1992) reported TP losses ranging from 0.02 to 4.39 kg ha^{-1} yr^{-1} from several grasslands in Oklahoma of varying land use and condition. While P losses from managed turf are similar to urban and agricultural P losses, side-by-side measurements tend to show elevated P losses from turfgrass areas compared to pristine areas. Winter and Dillon (2006) reported TP exported from four forests streams in Canada ranged from 0.02 to 0.15 kg ha^{-1} yr^{-1}, while TP export from streams transecting two golf courses ranged were 0.7 and 0.33 kg ha^{-1} yr^{-1}. A Japanese golf course was found have an average export of 2.1 kg DP kg ha^{-1} yr^{-1} over a two year period, while an adjacent forest exported only 0.05 kg DP kg ha^{-1} yr^{-1} (Kunimatsu et al., 1999). However, P discharge into the stream from a wastewater treatment plant on the golf course was not quantified.

Leaching Losses of Phosphorus in Turfgrass Systems

Leaching has been considered a minor pathway in many systems for P loss because most soils and subsoils have a high P sorption capacity relative to the amount of P applied (Sims et al., 1998). However, under the following circumstances P leaching can become a major pathway for P loss: fertilized soils with low P sorption capacity (Breeuwsma and Silva, 1992), soils with high organic matter (Duxbury and Peverly, 1978), soils with a large network of macropores (Geohring et al., 2001), and soils with elevated P levels in the upper profile caused by long-term or large additions of P (Heckrath et al., 1995). Each of these situations is not uncommon in turfgrass ecosystems.

Sand is a common construction material for golf course putting greens and athletic field root zones. In addition to having high infiltrability, sand-based root zones typically have very low P sorption capacities, receive soluble fertilizers, frequent irrigation, and have subsurface drainage. To date, the largest amount of research on P leaching from turfgrass systems has been conducted on sand-based root zones (Table 3). Results show that annual P-leaching losses from field studies of fertilized sandy soils ranged from 0.03 to 6.1 kg ha^{-1} (18.5 kg ha^{-1} in a greenhouse study) with P concentrations observed over 13 mg L^{-1}. Placement of P in sand greens (surface vs. subsurface) was found to have no significant effect on P leaching losses (Guertal, 2007). Although P losses from irrigated sand-based root zones should not be ignored, they account for approximately only 0.35% of all turfgrass areas, as sand-based root zones are confined to high-maintenance athletic fields and golf putting greens. Golf putting greens are usually less than 5% of the area of a golf course (Beard, 2001) and golf courses account for less than 7% of the total turfgrass area in the U.S., as estimated by Milesi et al. (2005) [assuming 16,000 golf courses in the U.S. (National Golf Foundation, 2003) with an average size of 70 ha].

Studies examining P leaching in finer-textured soils have found P losses ranging from 0.2 to 5.4 kg ha^{-1} (Table 3). Easton and Petrovic (2004) observed annual P leaching losses of 1.3 kg ha^{-1} for unfertilized turfgrass grown on a sandy loam. In their study, where P leaching loads were estimated from anion exchange resins buried in the soil, P loss increased with the P fertilization rate. Linde and Watschke (1997) observed leaching losses of 1.7 to 2.2 kg ha^{-1} after 28 simulated rain events over two years, with six of the events preceded by fertilizer applications. Most of the other studies indicate lower P leaching losses from finer textured soils ranging from 0.2 to 0.7 kg ha^{-1} (Table 3). The single watershed-scale study reviewed (King et al., 2006) found annual P-leaching losses to be 0.46 kg ha^{-1}. For many of the studies, soil P level is not reported and has not been examined as a factor that may influence P leaching. Petrovic (2004) found P leaching to be over three times greater from a silt loam than a sand loam or a sand soil; however, the amount of P leached from fertilized plots was lower than the P leached from the unfertilized control plots for all three soils. This research demonstrates the need for work on how sources other than that directly attributed to fertilizer (i.e., soil P) affect P leaching from turfgrass areas.

Models have predicted increasing soil organic matter content under well-maintained turfgrass systems (Milesi et al., 2005; Pouyat et al., 2006), and researchers have documented increases in soil organic matter in turfgrass systems over time (Porter et al., 1980; Qian and Follett, 2002). High soil organic matter content can also be expected where organic matter (such as compost) is intentionally added to improve soil physical properties. The use of composted manure to improve urban soils appears to be on the rise as animal feeding operations look for innovative ways to export large quantities of manure to meet government-specified water quality goals (Vietor et al., 2002, 2004; Cogger 2005). While some assessments have been made regarding the potential impact of runoff from imported sod on water quality (Richards et al., 2008), the effect on the elevated organic matter levels and soil P levels on P leaching losses has been ignored.

Soils that are infrequently disturbed, like those beneath turfgrass, are more likely to have continuous macropores than frequently disturbed soils. Large discrepancies in chemical transport have been documented between disturbed and undisturbed soil columns from a turfgrass system (Starrett et al., 1996). Macropores are formed by macrofauna (e.g., earthworms), plant roots, and soil physical processes such as shrink/swell, wet/dry, and freeze/thaw cycles (Beven and Germann, 1982). These pores enhance preferential flow and increase loss of chemicals normally considered to be relatively immobile in soils by bypassing the majority of pores in the soil matrix (Camobreco et al., 1996). In addition, preferential flow can occur at soil moisture levels much below saturation (Andreini and Steenhuis, 1990). Agricultural field research has observed greater than expected P loss in drainage due to preferential flow pathways (Heckrath et al., 1995, Beauchemin et al., 1998).

Based on the results shown in Tables 2 and 3, it is evident that the reported P-leaching losses are of the same scale as the reported P runoff losses in turfgrass systems. This finding substantiates the need for future research to document P-leaching losses from turfgrass areas, especially those managed similarly to lawns.

SOURCES OF PHOSPHORUS IN RUNOFF AND DRAINAGE FROM TURF

To effectively reduce soluble P losses from turfgrass, knowledge of sources and relative contributions to P in runoff from those sources is required. The three potential major sources of P in runoff from turfgrass include fertilizer, soil, and tissue.

Fertilizer

Application Timing

Application timing plays an important role in the fate of P fertilizer. A portion of the applied P is soluble in water and will be available to runoff. However, as the P dissolves, it is sorbed by the soil, rendering it much less available to runoff and leaching loss. Therefore the window between application and dissolution/sorption is critical. Kelling and Peterson

Table 3. Leaching losses of P from turfgrass systems.

Soil test P/ (method)	Soil type	Leachate collection method	P Source	P application rate	P concentration range in leachate (form)	P load	Loss of applied P (form)	Reference (form of P measured†)
kg ha^{-1}				kg ha^{-1} yr^{-1}	mg L^{-1}	kg ha^{-1} yr^{-1}	%	
NR¶	Sand (90% medium + fine sand)	40 cm deep field lysimeter	Superphosphate	25– 50‡	0– 0.2	0.03	No control	Lawson and Colclough, 1991 (MRP)
	2:1 sand: sandy loam				0–1.2	0.05	No control	
	Sandy loam				0–0.3	0.33	No control	
85/ (Mehlich 3)	Hagerstown clay, depth to bedrock 5– 60 cm (Typic Hapludalf)	15 cm deep field lysimeter	Monoammonium phosphate	6–11	0.41–4.92	1.7–2.2	No control	Linde and Watschke, 1997 (MRP)
NR	Sand	25 cm deep field lysimeter	Superphosphate	80	0.11–10.25	NR	NR	Engelsjord and Singh, 1997 (DRP)
16/ (Mehlich 1)	Sand	52.5 cm deep greenhouse lysimeter	Several	43 (6 mo.)	<0.1–13.5	6.5–18.5	15- 43	Shuman, 2003 (DRP)
		52.5 cm deep field lysimeter	Superphosphate	5	0.25–1.0	NR	5.4	
			Superphosphate	5	0.25–1.6	NR	8.1	
			Poly/Sulfur coated Superphosphate	11	0.25–0.6	NR	3.0	
			Poly/Sulfur coated Superphosphate	11	0.25–1.0	NR	6.5	
NR	Arkport sandy loam (Lamellic Hapludalf)	20 cm deep anion exchange resin	N/A	0	N/A§	1.3	NA	Easton and Petrovic, 2004 (DRP)
			Monoammonium phosphate	17	N/A	2.0	9.4	
			Monoammonium phosphate	42	N/A	1.9	3.3	
			Biosolids	67	N/A	1.7	1.4	
			Dairy compost	75	N/A	4.7	10.4	
			Swine compost	94	N/A	5.4	10.0	
NR	Sand	37 cm deep field lysimeter	Monoammonium phosphate	2.1	Max = 0.19	0.2	Less than control	Petrovic, 2004 (DRP)
NR	Arkport sandy loam (Lamellic Hapludalf)		Monoammonium phosphate	2.1	Max = 0.11	0.2	Less than control	
NR	Hudson silt loam (Glossaquic Hapludalf)		Monoammonium phosphate	2.1	Max = 0.12	0.7	Less than control	
NR	Sand	75 cm deep field lysimeter	Monoammonium phosphate	16	0.1– 2.2	6.1	No control	Erickson et al., 2005 (TDP)
NR	Gravelly loamy sand over sandy clay	Drainage outlet from golf course	NR	22	<0.07– 0.99	0.46	No control	King et al., 2006 (DRP)

†DP, dissolved phosphorus; DRP, dissolved reactive phosphorus; MRP, molybdate reactive phosphorus; TP, total phosphorus.

‡6 kg/ha applied in year 1, 11 kg/ha in year 2.

¶NR; not reported.

§NA, not applicable.

(1975) observed that 10.6% of an applied commercial lawn fertilizer was lost when followed immediately by an intense simulated rain event (90 min, 120 mm h^{-1}). However, by applying a light amount of water without causing runoff, commonly called watering-in, before the simulated storm, average fertilizer loss was reduced by an order of magnitude. Similar results were obtained by Shuman (2004), who found that watering-in reduced P loss compared to not watering-in the fertilizer. This phenomenon has also been observed in studies collecting natural runoff. For example Gaudreau et al. (2002) found greater runoff-P losses from turfgrass treated with composted manure or inorganic P fertilizer compared to control plots when runoff occurred within 3 d of application. However, for the remainder of the runoff events (occurring 27–87 d after treatment), differences in P loss between the treatments were smaller. Easton and Petrovic (2004) found nutrient concentrations in runoff were always highest during the first runoff event following fertilization.

Application Rate

Easton and Petrovic (2004) applied five different P fertilizers at the same annual rate on a sandy loam soil, but divided the annual application into two or four separate applications. The treatments that received the twice yearly application resulted in an average increase in P loss in runoff of 4.8%, and a 59% increase in P loss in leachate compared to the treatments applied four times per year. These results suggest that individual fertilizer application-rate influences drainage losses to a much greater extent than runoff losses—likely because drainage volume was much greater than runoff volume for that particular soil. Other studies have found P loss in drainage to be directly related to P application rate (Shuman, 2001; 2003). When a rain simulator was used to force runoff 4, 24, 72, and 168 h after fertilizer application, Shuman (2002) found P concentrations in runoff to vary directly with fertilizer rate. In Texas, Gaudreau et al. (2002) also found runoff-P loss to vary directly with application rate for both inorganic and organic sources of P during a two-year study during which four natural runoff events occurred.

Fertilizer Source

In addition to application timing and application rate, the source of P in fertilizer has been shown to influence P loss in runoff and drainage. Shuman (2001; 2003) found that a soluble inorganic source of P (monoammonium phosphate) was more prone to leaching losses through a sand-based root zone than a controlled release fertilizer (a soluble fertilizer coated with sulfur or a polymer to reduce solubility). However, it is unknown if differences between soluble and controlled release products would be detected on a mineral soil, or if differences in runoff losses of P would be evident between soluble and controlled-release products.

Probably the more important factor is the difference between inorganic and organic sources of P. With few exceptions, lawns are fertilized with a complete fertilizer containing N, P, and K. Because N is the most limiting nutrient for turfgrass growth and quality, universities (and lawn fertilizer manufactures) will recommend the fertilizer be applied to achieve an application rate of 0 to 73 kg N ha^{-1} mo^{-1} for warm season grasses and 0 to 39 kg N ha^{-1} mo^{-1} for cool season grasses depending on grass species and expected use (Carrow et al., 2001). Therefore, the amount of P applied to turfgrass is dependent on the fertilizer's N:P ratio. Gaudreau et al. (2002) found greater runoff losses from inorganic sources than sod fertilized with dairy manure at a rate of 100 kg ha^{-1}. Similarly, Vietor et al. (2004) found sod grown on composted dairy manure to have greater runoff P losses than unfertilized turfgrass, but similar losses to conventionally fertilized turfgrass.

In reality, homeowners apply fertilizer to meet N requirements, and therefore rate and source are difficult to separate. When organic sources of fertilizer are used, although less soluble, they will likely be applied at higher rates than conventional lawn fertilizers (often with $N:P_2O_5 > 10$), which can result in greater total P losses (Easton and Petrovic, 2004). When fertilizer or compost with a small N:P ratio is applied, over time soil P levels will elevate, potentially becoming an important source of P in runoff and drainage water. Soldat and Petrovic (2007) found compost applied to turfgrass at rates intended to change soil physical properties (up to 24 mm yr^{-1}) resulted a dramatic increase in soil P levels, which led to increased runoff P losses (Soldat et al., 2008). Organic sources are also known to vary in availability of P to runoff or leaching losses, meaning organic sources with similar P content can have different effects on P concentration in runoff and drainage (Ebeling et al., 2003).

Soil

In agriculture, it has been acknowledged that soil P levels influence P concentrations in runoff (Sharpley, 1995) and drainage (Heckrath et al., 1995). Soil test P levels have been shown to be linearly related to P concentrations in runoff from agriculture. Some soils have been shown to exhibit a threshold level of soil test P above which P concentrations in runoff and drainage increase at a greater rate than below it. This phenomenon occurs because of the sorption properties of the soil, which are influenced by texture, mineralogy, and management practices. Soils with elevated P levels that may be prone to excessive runoff or leaching losses are common in systems where inputs (fertilizers, compost, manure, etc.) greatly exceed outputs (crop removal) over the long-term.

Despite the known importance of soil P level on runoff and drainage losses in agriculture, the effect of soil P level on P losses in turfgrass systems is largely unknown. Barten and Jahnke (1997) found a poor correlation (r^2 = 0.15) between soil test P and P in runoff from turfgrass across a range of 7 to 73 kg ha^{-1} Bray-1 P. Vietor et al, (2004) found runoff total-dissolved-phosphorus (TDP) losses to be directly related to acidified ammonium acetate-extractable soil P. Similarly, Soldat et al. (2008) found soil test level was an adequate predictor of P in runoff from turfgrass across a very wide range of soil P levels, with the highest soil P levels related to large applications of manure-based compost applications. However, across the range of soil test levels common to home lawns in NY, soil test level was not a good indicator of P concentration in runoff caused by large variance in the relationship between soil P and runoff P at relatively low soil P levels (<50 mg kg^{-1} Morgan-extractable soil P). In agriculture, management plays a very large role in determining how soil P affects P loss. Turfgrass management practices differ greatly from those used in agriculture and it will be necessary to understand these relationships to more effectively reduce P losses from turfgrass areas.

To realize the relative potential contribution from turfgrass soils in our urban watersheds, more information is needed on actual soil P levels for turfgrass areas in the U.S. A very limited amount of data currently exists, most analyzed from the relatively small amount of unsolicited (non-random) soil samples sent into testing labs for analysis. These surveys tend to report that well over half of the lawns have soil P levels above the research-based optimum level required for growth.

Tissue

Although direct measurement has yet to be done of the contribution that plant tissue makes to P runoff from turfgrass areas, plant tissue has been shown to contribute significantly to P in runoff from other crops such as cotton (Sharpley, 1981) and pasture grass (McDowell et al., 2007). A relatively large amount of P can be concentrated above-ground in turfgrass areas. At any one time, a typical amount of above-ground turfgrass biomass might be 10,000 kg ha^{-1} (Lush, 1990). Turfgrass leaf tissue usually contains 0.20 to 0.50% P by weight (Guillard and Dest, 2003; Johnson et al., 2003; Miller and Thomas, 1999), meaning 20 to 50 kg ha^{-1} of P exists above-ground, up to 5 to 10% of which may be water soluble (Tukey, 1970; Sharpley, 1981) and therefore potentially available to runoff. These figures represent the constant above-ground biomass and do not take into account clipping production, which can amount to a significant increase in tissue P available to runoff or leaching. Kussow (2004) observed that freshly mown *P. pratensis* L. shoots contain 0.6 kg ha^{-1} of water soluble P, an amount that could account for a very substantial portion of the observed runoff losses summarized in Table 2. Water soluble P increased when the turfgrass tissue was dried and frozen. However, limited field research to date has not shown greater P losses from plots where clippings are returned compared to those where clippings are removed (Kussow, 2008)

KNOWLEDGE GAPS AND FUTURE RESEARCH NEEDS

The effect of turfgrass on water quality is an important issue that deserves further study. Several research opportunities have been identified in this review to increase our understanding of P loss and provide effective strategies for reducing P loss from urban and suburban areas. Perhaps the first priority is to collect accurate information on the turfgrass management practices (fertilization rates, timing, sources, clipping management, and irrigation) of homeowners and how they relate to soil properties and soil P levels of urban areas. This information will be useful in identifying where immediate gains can be made through educational outreach programs.

Future research should focus on the spatial and temporal variability of runoff from turfgrass areas and urban ecosystems in general. The results from these studies would be more useful in developing targeted BMPs for reducing P loss than plot-scale studies which are confined to a specific location in a watershed. The importance of understanding spatial and temporal runoff processes from turfgrass have been emphasized (Easton and Petrovic, 2008; Kussow, 2008), yet more work is needed to be able to accurately predict P losses from turfgrass areas. Because turfgrass areas account for the majority of pervious area in urban ecosystems, the infiltration characteristics of the turfgrass areas affect the hydrology of the urban watershed. Previous research has highlighted the major impacts that home construction can have on the infiltrability of turfgrass areas. Future research should focus on techniques that will allow modern home construction practices to continue without significantly reducing soil infiltrability. As suburban areas continue to expand in the U.S., opportunities for implementing watershed-scale research should be relatively easy to identify in many areas throughout the U.S.

Future research efforts should also focus on the relative contribution of P from fertilizer, soil, and tissue to runoff and drainage losses from turfgrass under a range of soil types and management regimes (especially irrigation impacts). The effect of soil P level on P in runoff and leaching has particularly been ignored and should be examined in more detail. Information generated by these studies will be helpful for developing BMPs for achieving reductions in P loss from turfgrass areas.

CONCLUSIONS

Annual fertilizer inputs were estimated to be 2 to 10 kg ha^{-1} based on a review of the analysis of typical commercial lawn fertilizers and common homeowner fertilization practices. These fertilizer inputs are slightly greater than the outputs from clipping removal (0.4–7.5 kg ha^{-1} yr^{-1}), estimated from homeowner surveys. Because of the large and expanding amount of turfgrass in the U.S., more information should be collected regarding homeowner lawn-maintenance practices to help assess the water quality risk associated with lawn maintenance. Unbiased (random) information regarding soil P levels of lawns is particularly lacking.

Runoff and leaching losses of P have been shown to be very high when runoff or drainage occurs shortly after a P fertilizer application, with up to 18% of the applied fertilizer being subject to loss. Research has identified several effective strategies for minimizing losses associated with P losses following fertilization. These include (i) applying P fertilizer only when need is indicated by a soil test, (ii) lightly "watering-in" P fertilizer to speed dissolution into soil, (iii) withholding P application before large expected rain events, and (iv) constructing wetlands to attenuate stormwater flow and reduce P export from large turfgrass areas.

A review of the literature found that sediment loss from established turfgrass areas is very low, even in relatively low-density turfgrass stands. Studies collecting runoff from natural rainfall or snowmelt events have found that P losses from fertilized and unfertilized turfgrass areas are generally <1 kg ha^{-1} yr^{-1}. These losses are not dissimilar to inputs of atmospheric deposition in urban areas, shown to be between 0.15 and 0.77 kg P ha^{-1} yr^{-1}.

Leaching losses of P can be substantial in fertilized soils with a low P sorption capacity, like sand. However, the few studies that measured leaching losses from finer-textured soils (greater P sorption capacities) have found them to be similar in magnitude to runoff losses. This suggests that more work is required to understand the potential impact of P leaching on water quality from turfgrass areas, particularly the effect of soil P on P loss. In addition, future research should also focus on the spatial and temporal variability of P losses from turfgrass areas.

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