Surface Water Quality

Fertilizer Source Effect on Ground and Surface Water Quality in Drainage from Turfgrass

Zachary M. Easton* and A. Martin Petrovic

ABSTRACT

Nutrients in surface and ground water can affect human and aquatic organisms that rely on water for consumption and habitat. A mass-balance field study was conducted over two years (July 2000–May 2001) to determine the effect of nutrient source on turfgrass runoff and leachate. Treatments were arranged in an incomplete randomized block design on a slope of 7 to 9% of Arkport sandy loam (coarse-loamy, mixed, active, mesic Lamellic Hapludalf) and seeded with Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.). Three natural organic (dairy and swine compost and a biosolid) and two synthetic organic nutrient sources (readily available urea and controlled-release N source sulfur-coated urea) were applied at rates of 50 and 100 kg N ha^{-1} per application (200 kg ha^{-1} yr^{-1}). Runoff water collected from 33 storms and composite monthly leachate samples collected with ion exchange resins were analyzed for nitrate (NO_3^-–N), phosphate (PO_4^{3-}–P), and ammonium (NH_4^+–N). Nutrient concentrations and losses in both runoff and leachate were highest for the 20-wk period following turfgrass seeding. The NO_3^-–N and NH_4^+–N losses declined significantly once turfgrass cover was established, but PO_4^{3-}–P levels increased in Year 2. Turf's ability to reduce nutrient runoff and leachate was related to overall plant growth and shoot density. The use of natural organics resulted in greater P loss on a percent applied P basis, while the more soluble synthetic organics resulted in greater N loss.

Both nitrogen and phosphorus pose a risk to surface water at relatively low levels (Sharpley et al., 1994; Parry, 1998). Phosphorus is responsible for algal blooms in surface waters (Bush and Austin, 2001) and can cause eutrophication at levels as low as 0.01 to 0.035 mg L^{-1} (Mallin and Wheeler, 2000). In coastal estuaries, NO_3^-–N can be a limiting factor for eutrophication and algal blooms and responsible for impaired habitat (Valiela et al., 1997). Nitrogen is applied in the largest quantities since it is generally the limiting agent to growth and quality. Nitrate is the most mobile nutrient generally applied to turfgrass (Watschke et al., 2000) and is, therefore, a risk to ground water contamination. Fertilization practices on turfgrass are a potential source of ground and surface water contamination because of intensive management and extensive acreage under cultivation (Petrovic, 1990).

Turfgrass can, however, be a very effective filter. The dense growth habit and thatch-forming capabilities of turfgrass create a tortuous pathway slowing runoff velocities, reducing sediment loss, and increasing infiltration (Linde et al., 1995, 1998). The turfgrass canopy reduces erosion by dissipating rainfall impact energy, which reduces sediment detachment (Krenitsky et al., 1998), and subsequent transport of ions such as phosphate, explaining why the bulk of P transport is in the soluble form (PO_4^{3-}–P) and total soluble P (Gross et al., 1990). Furthermore, a dense stand of turfgrass such as Kentucky bluegrass is highly efficient at removing water from the soil (Ebdon et al., 1999), which lowers runoff and leaching potential by reducing soil moisture. Evapotranspiration is generally the largest source of soil water removal in a turfgrass ecosystem in temperate regions. This results in removal of soil solution nutrients by the turfgrass, generally the largest sink for nutrients in the turfgrass ecosystem (Petrovic, 1990). Kentucky bluegrass has been shown to sequester up to 50% of applied N and 88% of applied P in harvested sod (Vietor et al., 2002), depending on the amount of fertilizer applied.

Correct fertilization practices do not, in general, cause excessive nutrient losses from turfgrass. Gross et al. (1990) found runoff losses of NO_3^-–N from turf to be low (<1% of applied fertilizer). In a short-term field study conducted by Miltner et al. (1996), very low levels of ^{15}N-labeled urea were recovered in leachate, representing only 0.23% of the applied N. Other N losses include denitrification, volatilization (3.3–21.3%), and plant uptake (29.5%), as well as soil storage (2.1–10.6%) (Horgan et al., 2002).

However, in some cases nutrient concentrations and losses can be excessively high. In most of these cases, environmental factors such as rainfall in winter (Snyder et al., 1984) and saturated soils (Baird et al., 2000) are related to high losses. In other cases fertilizer solubility was shown by Brown et al. (1977) to play a large role in controlling N loss in leachate. Sources with high solubility such as NH_4NO_3 produced substantially higher NO_3^-–N concentrations in leachate than less soluble sources like a biosolid or urea formaldehyde.

Manures and composts, through elevated P content, have the potential to negatively affect water quality (Ebeling et al., 2002). Gaudreau et al. (2002) measured P loss in runoff from turfgrass treated with 50 and 100 kg ha^{-1} manure, well above 2 mg L^{-1}. Baird et al. (2000) found that NH_4^+–N levels in runoff water from turfgrass filtered through buffers of greater than 7 mg L^{-1} and NO_3^-–N levels of 4 mg L^{-1} (USEPA maximum contaminant level for NO_3^-–N is 10 mg L^{-1}). Upwards of 6% of NH_4^+–N and 4% NO_3^-–N was lost in single runoff events, indicating that the ability of a buffer to capture

Department of Horticulture, Cornell University, Ithaca, NY 14853.
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*Corresponding author (zme2@cornell.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

soluble N is directly related to its ability to control runoff. However, the effect of concentrations such as those above may be reduced by further dilution within the ecosystem.

Establishment is perhaps the most problematic time for water contamination. The combination of little ground cover, high application rates of soluble fertilizers, and frequent irrigation can create situations prone to runoff and leachate losses. Snyder and Cisar (2000) recorded NO_3^-–N levels of 20 to 200 mg L^{-1} in leachate from newly established bermudagrass lysimeters. They found nitrate loss from the established turf was much lower (<10 mg L^{-1}). Bowman et al. (1998) found NO_3^-–N concentrations under shallow rooted turf to be significantly higher (26.5 mg L^{-1}) than concentrations under deeper, more extensive root systems (13.5 mg L^{-1}). In a study by Rosenthal and Hipp (1993), extremely high NO_3^-–N levels (>300 mg L^{-1}) were measured in runoff from turfgrass, which is not unusual at establishment. However, despite high runoff concentrations, mass losses are generally greatest in leachate. In his review of the fate of nitrogenous fertilizers, Petrovic (1990) reports up to 84% of applied N was recovered in leachate.

Many other factors directly unrelated to fertilizer application are important to consider when assessing potential nutrient losses. Sandy soils are prone to P loss because of reduced fixation capacity and rapid water percolation (Harris et al., 1994). However, sandy soils generally reduce runoff through increased infiltration. Akhtar et al. (2003) found that soils with macropores had a much higher P loss than sandy soils. Starrett et al. (1995) recovered up to 10% of N applied to turf-covered soil columns within a few hours of application, attributed to NO_3^-–N mobility in the soil due to the presence of macropores extending past the root zone. Turner and Haygarth (2000) found P concentrations of 0.5 mg L^{-1} in drainage from lysimeters packed with silty clay very shortly after water application because of preferential flow through cracks in the clay. High soil moisture levels caused by prolonged periods of rainfall or irrigation can be responsible for large runoff and nutrient losses even on established dense turfgrass (Linde et al., 1995).

This study was initiated to (i) determine if fertilizer properties (natural organic vs. synthetic organic, slow release vs. water soluble) and rate would affect ground and surface water quality in drainage from turfgrass, through a mass-balance approach and (ii) determine what factors, other than those related directly to fertilizer source or rate, can affect surface and ground water quality resulting in water contamination.

MATERIALS AND METHODS

The experimental plots were established in July 2000 on an Arkport sandy loam by treating existing turf with glyphosate [N-(phosphonemetyl)glycine] at a rate of 7.9 kg ha^{-1}. Sod was stripped, the seed bed prepared, and an 80:20 (% w/w) mix of Kentucky bluegrass ('Langara') and perennial ryegrass ('Prelude,' 'Palmer,' 'Repel') seed was sliced in at a rate of 146 kg ha^{-1}. Treatments, consisting of five fertilizer sources applied at two rates, and an unfertilized control were applied (Table 1) to plots 1 m wide and 2 m long and situated on a 7 to 9% slope with length parallel to slope. Experimental plots, seeded on 18 July 2000, received a total of 200 kg N ha^{-1} in both 2000 and 2001. Fertilizers were applied at a rate of 50 kg ha^{-1} on 18 July, 22 Aug., 24 Sept., and 30 Oct. 2000 and 24 May, 11 July, 27 Aug., and 20 Oct. 2001. Plots receiving the 100 kg N ha^{-1} rates (twice the normal application rate) were fertilized on 18 July and 25 Sept. 2000 and on 24 May and 27 Aug. 2001. Analysis for the natural organics is reported as elemental N, P, and K. Fertilizers were applied by hand to the turf and watered in with 5 mm of irrigation. The control treatment was unfertilized. Runoff collection trenches were built on the down-gradient side of each plot following the protocol similar to that used by Cole et al. (1997). Plots were edged with a 2.5-mm stainless steel border, installed at a depth of 8 cm to prevent up-slope runoff from entering the experimental area.

Turfgrass shoot density was measured eight times during the study period at 6-wk intervals during the growing season. A counting grid (58 cm^2 per grid) was placed on the turf, and shoots were counted in three randomly selected areas of each plot. Results were averaged for each plot to determine density (shoots m^{-2}). The soil infiltration rate was determined in August 2001 using the method outlined by Bouwer (1986). The steady state infiltration rate was then determined from the infiltration test data using the Green–Ampt equation (Risse et al., 1994). Use of the Green–Ampt method assumes that the soil was initially unsaturated, an assumption that was verified by gravimetric water content measurements at the time of the infiltration rate tests. Soil hydrometer analysis was performed before site establishment, with the 40-s silt and clay and 2-h clay methods used. Sand content was determined by subtracting the silt and clay fraction from 100%. Sand content at the site ranged from 43 to 70%, silt from 19 to 39%, and

Table 1. Fertilizer treatments applied to turfgrass. Experimental plots were seeded on 18 July 2000 and received a total of 200 kg N ha^{-1} in both 2000 and 2001.

Treatment	Source	N–P–K analysis	Information	P applied†
				kg ha^{-1}
Natural organic				
Swine compost	Bion Technologies (Cary, NC)	4.25–2–0	6.7:1 C to N ratio	23.6
Dairy compost	Bion Technologies	0.8–0.3–0	15.2:1 C to N ratio	18.8
Biosolid	Milorganite (Milwaukee, WI)	6–2–0	municipal solid waste	16.7
Synthetic organic				
Readily available	Lesco (Strongsville, OH) urea	35–3–5	33.85% urea, 1.15% ammonical N 3% P_2O_5 as $NH_4H_2PO_4$ 5% potash (K_2O) as muriate of potash	4.3
Controlled-release	Lesco sulfur-coated urea	24–5–11	10.80% sulfur-coated urea, 11.25% urea, 1.95% ammonical N 5% P_2O_5 as $NH_4H_2PO_4$ 11% potash (K_2O) as muriate of potash	10.5

† The P rate for a single application of fertilizer to the experimental plots receiving 50 kg N ha^{-1}. The P application rate for the experimental plots receiving 100 kg N ha^{-1} would double.

clay from 8 to 22%, where the down-slope plots had lower sand and higher clay content.

Before seeding, volumetric water content, porosity, bulk density, and percent saturation tests were conducted on saturated and unsaturated soil samples (Danielson and Sutherland, 1986; Gardner, 1986). During or directly following each runoff event, soil samples were taken randomly with a 4.75-cm-diameter, 10-cm-deep undisturbed soil core sampler, weighed wet, dried at 104°C for 48 h, and reweighed to determine water content, bulk density, and porosity. Core holes were filled with Arkport soil. Daily weather data collected included rainfall; humidity; calculated evapotranspiration; minimum, maximum, and average temperature; wind speed; solar radiation; heating, cooling, and growing degree days; and snowfall. Plots were irrigated to prevent dormancy.

Runoff water volume collected from 33 precipitation events was recorded in the field, and a 300-mL subsample was collected and frozen at -4°C until analysis. At establishment, sediment was observed in runoff from all plots. Samples were cloudy with fine sediment. Following establishment, sediment was observed regularly in runoff only from the control treatment. Cationic and anionic exchange resins (Dynambio LLC, Madison, WI) were installed monthly directly below the root zone (depths varied with depth of rooting) to capture nutrients and estimate leaching past the root zone. Gibson et al. (1985), Gibson (1986), Abrams and Jarrell (1992), and Siddique et al. (2000) used resins to evaluate P movement, and several authors (Binkley and Matson, 1983; Carlyle and Malcolm, 1986; DiStefano, 1986; Schnabel, 1983) have used resins to measure nitrogen leaching and availability in soil. Resins can accurately measure soil solution or available nutrients. Since resins were placed below the root zone in this study, soil solution nutrients were considered to be leachable and, thus, this method was used to estimate the potential maximum amount of nutrient leaching. Pretreatment of resins was done by agitating the resins for 10 min in 0.5 *M* sodium acetate and repeating. The resin strips were then installed by creating a slit in the soil at 45° and inserting the resin with care to completely reseal the disturbed soil and prevent preferential flow to the exchange resin. The resins were placed in different areas of the plots each time. Resins were removed after one month in the soil during the growing season. Care was taken to remove excess soil on the resin. Resins were left in the soil for the winter. Once removed the resins were desorped by agitation for 2 h in 0.5 *M* hydrochloric acid and the solution was collected. Desorption was repeated to ensure complete removal of ions. The solution was then frozen at -4°C until analysis. Surface area of the resin was calculated as the projection of the resin onto the soil surface.

Analysis of runoff and leachate (ion resin extracts) solution was performed with an inductively coupled argon plasma optical emission spectrometer (ICP–OES) (Thermo Jarrell Ash 975 Plasma Atomcomp with radial view; Thermo Elemental, Franklin, MA). Analysis of PO_4^{3-}–P can be considered to contain the majority of the dissolved (soluble) P (Sharpley et al., 1994). To remove particulate nutrients, water samples were filtered through a 2-μm cellulose filter. The initial results were obtained on a Dionex (Sunnyvale, CA) DX 500 ion chromatograph using an AS11 column and an eluent of 30 m*M* NaOH. To obtain more sensitivity, samples were also analyzed with the Alpkem 3000 flow analyzer (OI Analytical, College Station, TX) for the USEPA continuous flow phosphate method. The Alpkem Flow 4 analyzer (OI Analytical) was used for the USEPA nitrate segmented flow analysis (Method 353.2; USEPA, 1993a) and ammonium segmented flow analysis (Method 350.2; USEPA, 1993b) methods. The detection limits were 7 μg L^{-1} for NO_3^-–N and PO_4^{3-}–P and 10 μg L^{-1} for NH_4^+–N.

Clippings were collected weekly from plots mowed to 5 cm starting 25 d after establishment. Weekly samples were mixed on a weighted basis to form a monthly composite. Clipping tissue samples were dried at 65°C, weighed, and submitted for analysis to the Cornell Nutrient Analysis Laboratory (Department of Horticulture, Cornell University, Ithaca, NY) using the ICP–OES. Tissue samples were analyzed for P content using dry-ash tissue extraction, as explained by Greweling (1976), using a modification of quartz ashing tubes and 30% H_2O_2 as the oxidizing agent instead of 2 *M* HNO_3. Samples were then re-dried for 1 h at 450°C after which 0.5 mL of concentrated HCl was added to the dried ash to re-solubilize the tissue, which was then diluted to a volume of 10 mL and analyzed by ICP–OES. Tissue N content was analyzed using the Kjeldahl procedure (Wolf, 1982), with NH_4^+–N determined according to Reardon (1966).

Statistical Design and Analysis

Treatments consisting of five fertilizer sources applied at two N rates plus an unfertilized control were arranged in an incomplete randomized block design (ICRB). An ICRB design was needed to minimize the number of plots while allowing the use of soil infiltration rate as the blocking variable. Each of 17 blocks contained two plots directly adjacent to each other. There were three replicates of each treatment resulting in 33 plots. However, two separate sets of blocks had the same soil infiltration rate, resulting in 14 degrees of freedom (instead of 16) for the blocking variable. Infiltration rate was determined to be the best parameter to block since there was a systematic variation in infiltration based on hillslope position and soil particle distribution. Data were natural log transformed to remedy increasing error variance and nonnormality of residuals. Depth of runoff and concentrations and mass loses of nutrients in runoff and leachate were then analyzed, after transformation, by analysis of variance (ANOVA) using the general linear model (GLM) in SAS (SAS Institute, 2000). Type III sums of squares were used to determine the significance of the variables in the regression analysis. Initial ANOVA (with the GLM) of treatment and treatment block interactions effects revealed no significant differences; therefore, the regression analysis included variables as shown in Tables 2 and 6. A Fisher's protected least significant difference was calculated on the transformed data to determine significant differences between treatment means at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Runoff and Clipping Recovery

Runoff was influenced by many factors (Table 2). Precipitation ($p = 0.003$), soil infiltration rate ($p = 0.041$), soil moisture ($p = 0.048$), shoot density ($p = 0.034$), time ($p = <0.001$), and fertilizer treatment ($p = 0.035$) significantly affected runoff. Fertilization created higher shoot density and higher soil infiltration rates, lower soil moisture levels, and less runoff. Soil infiltration rate and soil moisture are to some extent a function of turfgrass growth, which is controlled by fertilization. The effect of growth, as measured via shoot density counts, on the amount of runoff was found to be strongly correlated with fertilizer treatment effects ($p = 0.006$) and infiltration rate ($p = 0.002$). Lower runoff losses generally reduced nutrient losses as well. Those fertilizer

Table 2. Analysis of variance (ANOVA) table for runoff depth and nutrient concentration in runoff from turfgrass. The ANOVA was performed by multiple regression analysis (on transformed data).

		p Value			
		Response			
Source of variation†	df	Depth	NO_3^-–N	NH_4^+–N	PO_4^{3-}–P
Treatment	10	0.035†	<0.001	NS	<0.001
Time	1	<0.001	<0.001	NS	<0.001
Time × treatment	10	0.006	NS	NS	0.020
Precipitation	32	0.003	0.004	<0.001	NS
Soil infiltration rate	14	0.041	0.035	0.014	NS
Shoot density	1	0.034	NS	0.001	NS
Soil moisture	32	0.048	NS	NS	NS
Density × treatment	9	0.006	0.045	0.023	NS
Density × soil infiltration rate	14	0.002	NS	0.008	NS
Density × precipitation	32	NS	0.028	NS	NS
Soil infiltration rate × density × precipitation	448	NS	0.002	NS	NS
R^2		0.87	0.91	0.86	0.81

† Source of variation is included in the model if significant at $\alpha \leq 0.05$. Main effects are included in the model if the interaction is significant at $\alpha \leq 0.05$.

treatments that promoted high shoot density and adequate growth had lower mass losses, due in part to the increasing infiltration rate. As shoot density doubled, the infiltration rate also increased, which reduced runoff by threefold (Fig. 1).

Table 3 contains the recorded runoff depths for each runoff event during the study. Runoff losses were on average higher during the establishment period (2000). Once adequate turfgrass density was established the percentage of rainfall as runoff decreased, despite higher actual runoff losses. In Year 2 (2001), very intense storms created high runoff depths but lower percentage losses. Snowmelt or runoff on frozen soils was 62.0% of the total runoff. Of the non-snowmelt runoff, nine runoff events accounted for 66.5% of the total runoff collected and >65% of the runoff nutrient loss. The first runoff event (16 Aug. 2000) produced the highest non-snowmelt runoff depth and by far the highest percent of precipitation as runoff, as well as some of the highest N and P concentrations (Fig. 2 and 3). This can be attributed to negligible turfgrass density. The largest storm, greater than a 50-yr return period (Hershfield, 1961), on 24 Sept. 2001 was 111.6 mm, but produced less runoff (2.4 mm) than the first storm. Generally, the largest runoff events occurred when the antecedent soil moisture levels were high, >40% of total soil porosity.

The establishment period (2000) clearly presents the highest risk to ground and surface water quality. With little turfgrass in place to remove water and the soil moisture levels approaching field capacity (data not shown), the majority of the nutrient loss from the 2-yr study occurred during the 20-wk establishment period following the first four fertilizer applications made 0, 33, 66, and 102 d following establishment (Table 4). A substantial portion of the loss was due to the first four runoff events. With little uptake of nutrients at establishment, excess N and P were easily transported from the soil surface. Nitrate losses were on average two to five times higher during establishment than following establishment (Table 5), which was directly correlated with turfgrass density (Table 6). This is consistent with work done by Quiroga-Garza et al. (2001) who found that established turf stands utilize and retain more NO_3^-–N in the root zone. Bowman et al. (1998) recorded NO_3^-–N concentrations from deep-rooted turfgrass to be one-half those of shallow-rooted stands due to increased plant uptake. They concluded the reduction in NO_3^-–N concentration was probably due to increased infiltration from root channeling and greater NO_3^-–N uptake from increased root surface area.

At times, the runoff from the unfertilized control contained the highest NO_3^-–N concentrations (Fig. 2). In Year 2, mass losses were significantly higher than the dairy compost at 100 kg N ha^{-1} and biosolid at 100 kg N ha^{-1} (Table 5). A similar trend was observed for NH_4^+–N concentrations (data not shown). In Year 2, the highest runoff depths were recorded for the unfertilized control plots (Table 5), which had the lowest shoot density, clipping dry matter production, and infiltration rate. The higher runoff observed is consistent with results presented by Linde and Watschke (1997). As a result, runoff losses from unfertilized control plots were generally as high or higher than from the other fertilizer treatments, especially in Year 2 (Table 5). The higher evapotranspiration rates associated with a dense vigorous turf will reduce soil moisture, allow more water to enter the profile, and hence reduce runoff (Linde et al., 1998). As the turfgrass shoot density increased (Fig. 1), both runoff and NH_4^+–N losses decreased, similar to findings by Gross et al. (1990, 1991) and Krenitsky et al.

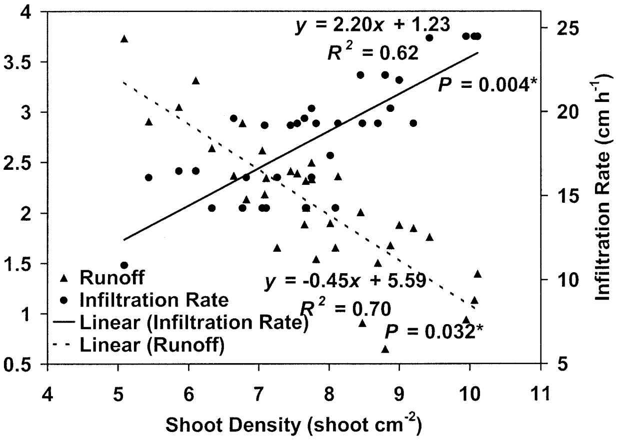

Fig. 1. Soil infiltration rate and runoff depth as a function of turfgrass shoot density. *Significant at the $\alpha = 0.05$ probability level.

Table 3. Runoff, rainfall depth, percentage of rainfall lost as runoff from turfgrass for each runoff event (site average), and corresponding turfgrass shoot density and soil moisture level.

Date	Runoff	Rainfall	Rainfall as runoff	Shoot density†	Soil moisture‡
	mm		%	shoot cm^{-2}	%
16 Aug. 2000	3.23	6.60	48.8	2.78	45.0
24 Aug. 2000	0.48	10.9	4.35		48.0
9 Sept. 2000	1.42	17.7	8.04		57.0
13 Sept. 2000	1.63	23.6	6.93	6.64	42.0
5 Oct. 2000	1.27	29.1	4.38		51.0
19 Oct. 2000	0.17	17.5	0.95	7.85	43.4
11 Nov. 2000	0.24	19.8	1.21		40.1
17 Dec. 2000	1.62	9.81	16.5		55.9
1 Feb. 2001	7.37§	2.79	¶		49.6
10 Feb. 2001	5.42§	0.00	¶		59.1
15 Feb. 2001	0.51§	0.00	¶		64.4
26 Feb. 2001	5.34§	1.78	¶		55.7
15 Mar. 2001	7.47§	8.12	91.9#		60.0
21 Mar. 2001	1.92§	0.00	¶		60.2
22 Mar. 2001	4.03§	0.76	¶		65.6
24 Mar. 2001	5.33§	0.00	¶		64.1
31 Mar. 2001	4.64§	0.00	¶		63.6
23 Mar. 2001	0.73	8.38	8.66	9.03	64.7
27 May 2001	0.20	11.6	1.72		59.4
3 June 2001	0.57	14.6	3.89		52.9
11 June 2001	1.29	23.5	5.50	9.42	52.5
17 June 2001	1.87	15.2	12.3		46.8
23 June 2001	1.73	48.3	3.58		51.7
1 July 2001	0.20	8.56	2.32		58.2
11 July 2001	1.63	26.4	6.16		60.4
17 July 2001	0.73	19.3	3.79		47.3
26 July 2001	0.66	12.6	5.22	7.68	47.6
3 Aug. 2001	0.93	8.13	11.4		60.1
17 Aug. 2001	0.90	29.5	3.07		52.7
20 Aug. 2001	1.10	20.1	5.49		59.1
28 Aug. 2001	0.89	18.0	4.94	9.27	52.4
24 Sept. 2001	2.41	111	2.16		68.3
30 Nov. 2001	0.23	11.9	1.92	9.81	56.4
Average	2.07	16.3	8.03	7.81	55.0
Total	68.1	536			

† Turfgrass shoot density for date corresponding to the closest runoff event. Density was measured every six to eight weeks during the growing season.

‡ Soil moisture content expressed as a percent of total porosity was measured physically by methods outlined by Gardner (1986) during or directly following each runoff event starting 11 Nov. 2000. Moisture content before 11 Nov. 2000 was determined with use of a Thornthwaite–Mather water balance as outlined by Steenhuis and Van Der Molen (1986).

§ Indicates runoff due to snow melt.

¶ For these runoff events precipitation was less than measured runoff due to snow melt, returning greater than 100% of precipitation as runoff.

Value 15 Mar. 2001 was left in place since the event involved both rainfall and snow melt.

(1998). The physical barrier the shoots created slowed runoff and allowed more water to enter the profile. Root turnover and deposition of organic matter reduced the bulk density of the soil, increasing total soil porosity, and allowed greater water storage and faster percolation. This is consistent with findings by Petrovic (1990),

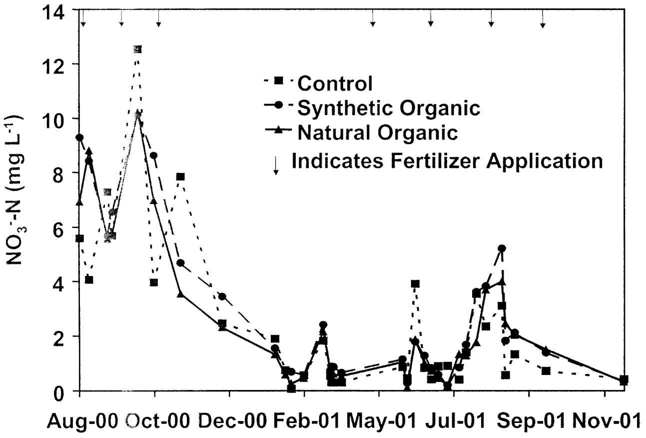

Fig. 2. Fertilizer source effects on nitrate concentrations in runoff from turfgrass. Natural organic (swine and dairy compost and biosolid) and synthetic organic (readily available and controlled-release) sources were averaged. Analysis indicates that there was a significant difference between NO_3^-–N concentrations in runoff by solubility at the $\alpha = 0.05$ level.

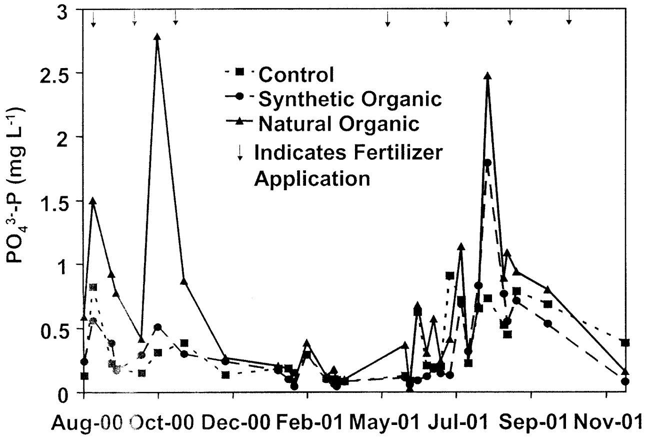

Fig. 3. Fertilizer source effect on phosphate concentrations in runoff from turfgrass. Natural organic (swine and dairy compost and biosolid) and synthetic organic (readily available and controlled-release) sources were averaged. Analysis indicates that there was a significant difference between PO_4^{3-}–P concentrations in runoff by solubility at the $\alpha = 0.05$ level.

Table 4. Percent of the total nutrients (PO_4^{3-}–P, NO_3^-–N, and NH_4^+–N) recovered in the two-year study found in runoff and leachate from turfgrass that was collected during establishment (July–December 2000).

Source	Fertilizer rate†	PO_4^{3-}–P lost in runoff	PO_4^{3-}–P lost in leachate	N lost in runoff	N lost in leachate
	kg N ha^{-1}	% of total			
Swine compost	50	24.2	50.2	57.3	64.6
Swine compost	100	26.8	59.8	50.6	59.1
Dairy compost	50	18.8	30.4	34.0	40.4
Dairy compost	100	17.3	55.6	44.7	50.5
Biosolid	50	15.0	17.8	53.8	77.8
Biosolid	100	14.5	14.2	67.9	73.3
Readily available	50	12.8	23.6	52.2	60.5
Readily available	100	13.8	16.9	70.6	79.7
Controlled-release	50	25.5	15.3	56.8	67.9
Controlled-release	100	24.4	18.2	68.7	75.0
Control	0	6.0	18.6	37.2	56.0
Fisher's LSD‡		6.4	9.7	11.5	12.0

† Single fertilizer application rate. Total yearly application was 200 kg N ha^{-1}, except for the unfertilized control.

‡ Treatments are significantly different if the difference between column means is greater than Fisher's protected LSD.

who reported that turfgrass growth may result in greater infiltration rates.

Source of fertilizer had a significant effect on both N and P concentrations in runoff. Readily available urea applied at 100 kg N ha^{-1} was the only fertilizer source that had a significantly higher NO_3^-–N concentration in runoff than the unfertilized control (Table 7). Only one fertilizer source (swine compost at 50 kg N ha^{-1}) produced significantly higher P concentrations than the unfertilized control, and only in the first year (Table 5). Mass loss of P in runoff was higher from all fertilizer sources except the readily available source, in the first year only. In the second year the unfertilized control had a significantly higher P mass loss than all other fertilizer sources, except swine compost at 100 kg N ha^{-1} (Table 5). The relatively high P losses from the natural organic sources were probably due to the higher P application rate. Since nutrients were applied on an N basis, P rates varied considerably; this may have resulted in P rates above plant needs. The higher application of P with the natural organic sources did not result in significantly higher P recovery rates in the tissue, despite an order of magnitude greater P application (Fig. 4A). This result could be explained by the different P release rates between natural organic and synthetic organic sources. The unfertilized control had the lowest mass of P recovered in the clippings, a result of reduced plant uptake, despite adequate soil P. Nitrogen losses generally followed solubility trends; synthetic organics (readily available and controlled-release) had more soluble N sources and higher N losses as observed by Brown et al. (1977).

Table 5. Time by treatment interactions shown for mean phosphate concentration and mass loss, nitrate mass loss, and runoff depth from turfgrass by treatment (fertilizer source and rate of application) for establishment (Year 1, July–December 2000) and post-establishment (Year 2, December 2000–January 2002).

Source†	Rate‡	Year	*n*	Runoff		PO_4^{3-}–P	NO_3^-–N
	kg N ha^{-1}			mm	mg L^{-1}	kg ha^{-1}	
Swine compost	50	1	24	1.09	2.4	0.8	8.2
Swine compost	50	2	58	2.40	0.9	1.0	2.9
Swine compost	100	1	24	1.30	0.9	1.2	6.0
Swine compost	100	2	62	2.18	0.7	1.2	3.0
Dairy compost	50	1	23	0.81	0.9	0.4	2.6
Dairy compost	50	2	59	2.81	0.5	0.7	2.9
Dairy compost	100	1	21	0.54	0.9	0.4	4.1
Dairy compost	100	2	54	1.85	0.7	0.7	2.5
Biosolid	50	1	24	1.06	0.8	0.4	8.7
Biosolid	50	2	59	2.44	0.6	1.0	4.4
Biosolid	100	1	23	0.87	0.3	0.2	8.5
Biosolid	100	2	52	2.14	0.6	0.6	2.5
Readily available	50	1	23	0.94	0.3	0.2	11.2
Readily available	50	2	64	2.26	0.3	0.6	3.1
Readily available	100	1	23	0.91	0.5	0.3	15.9
Readily available	100	2	52	2.45	0.5	0.6	4.1
Controlled-release	50	1	24	1.44	0.4	0.5	7.6
Controlled-release	50	2	60	2.36	0.4	0.6	4.3
Controlled-release	100	1	24	1.70	0.3	0.6	10.5
Controlled-release	100	2	61	2.54	0.3	0.7	2.8
Control	0	1	32	1.05	0.3	0.2	5.6
Control	0	2	91	3.34	0.5	1.3	3.8
Fisher's LSD§				1.78	0.8	0.1	1.2

† All treatments except the unfertilized control received a total of 200 kg N ha^{-1} yr^{-1}.

‡ Single fertilizer application rate.

§ Treatments are significantly different if the difference between column means is greater than Fisher's protected LSD at $\alpha \leq 0.05$.

Independent of source, all fertilizers produced the highest nutrient concentration in the first runoff event following application, generally with in 20 d (Fig. 2 and 3). The highest concentrations of NO_3^-–N of 12.5 mg L^{-1} were detected in Year 1 on 5 Oct. 2000 for the unfertilized control. On 24 Aug. 2000 the highest NO_3^-–N levels in runoff for the controlled-release and readily available treatments at 50 kg N ha^{-1} were detected following fertilizer application on 22 Aug. 2000. The NH_4^+–N concentrations in runoff were highest following the 22 Aug. 2000 fertilizer application, at 15.5 mg L^{-1}. Subsequent runoff events generally exhibited dramatic reductions in nutrient concentrations of the runoff, similar to results in a study by Linde and Watschke (1997).

The largest nutrient sink was clippings for P (Fig. 4A) and leachate for N (Fig. 4B). Of the total P recovered, clippings were responsible for sequestering between 58 and 88% of the total measured P loss. Removal of clippings resulted in a portion of plant-available nutrients being removed from the system. Starr and DeRoo (1981) measured 15% more N in the soil, thatch, and tissue when clippings were returned. The unfertilized control exhibited the lowest measured P, while the synthetic organic sources had the highest recovery. The measured P recovery of the unfertilized control was significantly lower than all other treatments, presumably

Table 6. Analysis of variance (ANOVA) table for nutrient mass losses in runoff and leachate from turfgrass. The ANOVA was performed by multiple regression analysis.

		p Value					
		Response					
		Runoff			Leachate		
Source of variation†	df	NO_3^-–N	NH_4^+–N	PO_4^{3-}–P	NO_3^-–N	NH_4^+–N	PO_4^{3-}–P
Treatment	10	NS†	<0.001	NS	<0.001	0.045	0.034
Time	1	NS	NS	0.010	0.034	0.003	NS
Time × treatment	10	0.004	NS	0.009	0.003	<0.001	<0.001
Precipitation	32	<0.001	<0.001	<0.001	NS	NS	0.003
Soil infiltration rate	14	NS	NS	NS	NS	0.007	NS
Soil moisture	32	0.034	<0.001	NS	<0.001	<0.001	<0.001
Porosity	32	NS	NS	NS	NS	0.024	NS
Density × soil infiltration rate	14	0.005	NS	NS	NS	NS	NS
Porosity × soil infiltration rate	448	NS	NS	NS	NS	0.011	NS
Precipitation × soil infiltration rate	448	NS	<0.001	0.010	NS	NS	NS
Time × density	14	<0.001	NS	NS	0.027	NS	NS
Density × treatment × soil infiltration rate	140	<0.001	NS	0.005	NS	NS	NS
R^2		0.87	0.84	0.80	0.81	0.91	0.81

† Source of variation is included in the model if significant at $\alpha \leq 0.05$. Main effects are included if the interaction is significant at $\alpha \leq 0.05$.

due to the lack of P application, and no N, which enhances growth and uptake of other nutrients. Clippings were responsible for somewhat lower N recovery than P, ranging from 26 to 52% of the measured N loss. The overall N-recovery rates were significantly higher for the readily available and controlled-release treatments at 100 kg N ha^{-1} (close to 65 and 55% of applied, respectively).

The differences in nutrient mass recovery were generally due to differences in clipping production, not nutrient composition of the clippings. In general, the fertilized treatments that produced much higher density and faster growth had greater clipping weight, which resulted in greater N and P removal and storage.

Nutrient Leaching

Nutrient leaching was found to be a function of fertilizer source, time, soil infiltration rate, shoot density, and antecedent soil moisture (Table 6). During the period directly following site establishment, the nutrient mass losses (especially N) in leachate were the highest observed, but in a 30-d period fell to low levels (Fig. 5A and 5B). During this period turfgrass shoot density increased dramatically (Table 3, Fig. 1), as did root depth and plant recovery of the nutrients.

Table 7 shows the amount of nutrient losses in leachate for Year 1 and Year 2. Mean NO_3^-–N leachate losses were extremely high in Year 1, fluctuating from 15.5 kg ha^{-1} for dairy compost at 50 kg N ha^{-1} to 186.5 kg ha^{-1} for the readily available treatment at 100 kg N ha^{-1}. For all sources but swine compost, doubling the single fertilizer application rate to 100 kg N ha^{-1} produced NO_3^-–N losses in leachate one and a half to four times higher than the 50 kg N ha $^{-1}$ treatments in Year 1. In Year 2, NO_3^-–N losses were much lower and none were significantly different than the unfertilized control (Table 8). In Year 1, all sources except the dairy compost at 50 kg N ha^{-1} allowed more NO_3^-–N to leach, producing mass losses significantly higher than the unfertilized control. In Year 1 all sources except swine compost had significantly higher mass losses of NH_4^+–N than the unfertilized control. However, in Year 2, only the dairy compost applied at 50 and 100 kg N ha^{-1} had NH_4^+–N losses significantly higher than the control. In this and other studies, NO_3^-–N was a much larger proportion of the N measured in runoff and leachate than was NH_4^+–N (Table 8). Toxic in surface waters, but rapidly converted to NO_3^-–N in soils, NH_4^+–N is in an intermediate, short-lived form in soils, and generally considered a minor source.

The swine compost at 50 and 100 kg N ha^{-1} and the dairy compost at 100 kg N ha^{-1} had significantly higher PO_4^{3-}–P mass losses than the unfertilized control in Year 1 (Table 8). All other fertilizer treatments were not significantly different from the unfertilized control in Year 1. In Year 2 there were no significant differences in P losses among fertilizer treatments. The higher losses from the composts (especially at 100 kg N ha^{-1} rate) can be at least partially attributed to application rate, where the composts had two to six times more P applied than the other sources. In addition, organic P (such as in manures and composts) is not fixed as rapidly and is, therefore, more prone to leaching loss (Robbins et al., 2000), which may explain the generally higher P leaching from the composts.

Table 7. Influence of fertilizer source and rate on mean NO_3^-–N concentrations in runoff from turfgrass for pooled data (Years 1 and 2).

Source	Rate†	*n*	NO_3^-–N
	kg N ha^{-1}		mg L^{-1}
Swine compost	50	82	2.7
Swine compost	100	86	2.4
Dairy compost	50	82	2.3
Dairy compost	100	75	3.8
Biosolid	50	83	2.3
Biosolid	100	75	4.2
Readily available	50	87	3.5
Readily available	100	76	4.8
Controlled-release	50	84	2.4
Controlled-release	100	85	2.8
Control	0	123	2.9
Fisher's LSD‡			1.5

† Single fertilizer application rate for a total of 200 kg N ha^{-1} yr^{-1}.

‡ Treatments are significantly different if the difference between column means is greater than Fisher's protected LSD at $\alpha \leq 0.05$.

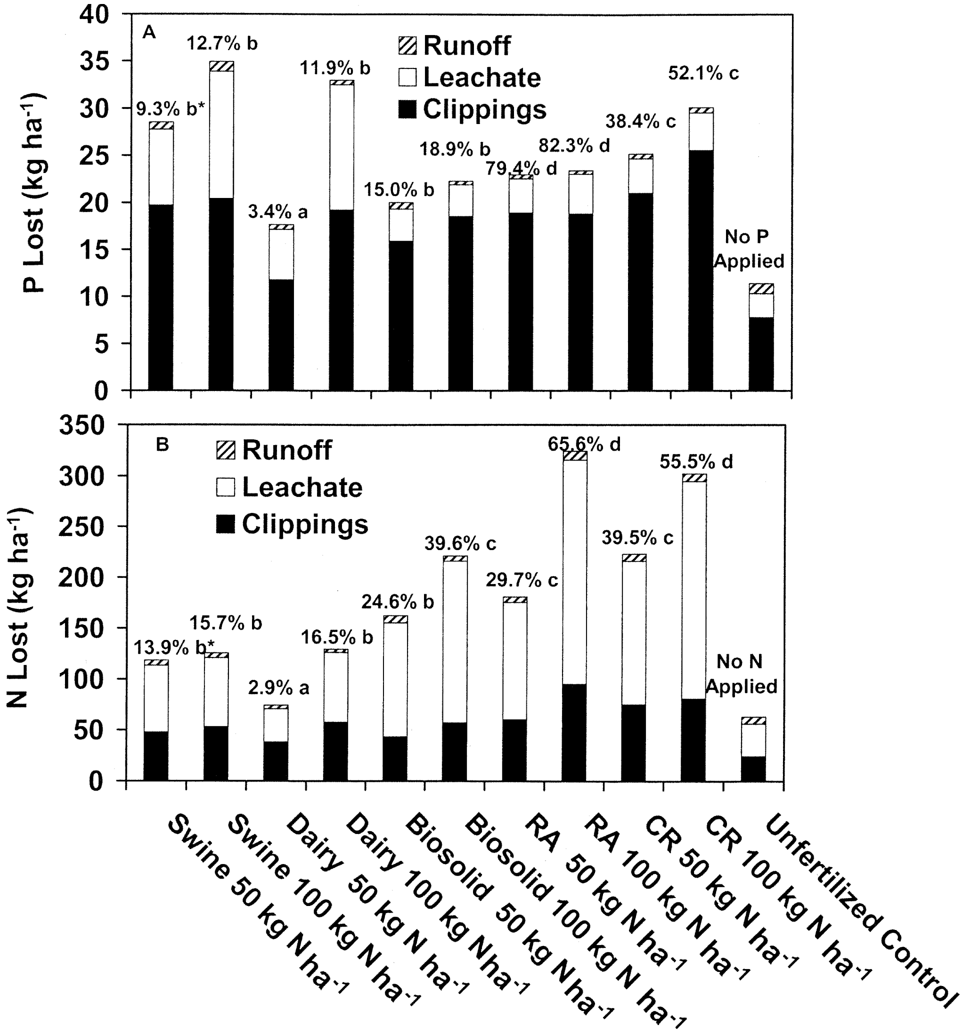

Fig. 4. Mass balance for (A) phosphorus and (B) nitrogen. The percent shown above each bar is the nutrient recovered rate in runoff, leachate, and clippings as a percent of applied after correcting for losses from the unfertilized control. The N rate shown for each source was the single application rate; total yearly N rate was 200 kg N ha^{-1}. *Percentages followed by the same letter are not significantly different at $\alpha = 0.05$. CR, controlled-release; RA, readily available.

Table 4 shows the percent of the total nutrient lost in leachate that occurred during establishment (Year 1). The swine and dairy composts at 50 and 100 kg N ha^{-1} lost significantly more P in leachate than the control during establishment. The biosolid at both rates and readily available and controlled-release treatments at 100 kg N ha^{-1} all had N losses at establishment significantly higher than the unfertilized control. The high overall losses in leachate during establishment would indicate that leaching has the potential to contribute significantly to ground water contamination when there is little ground cover in place.

Both the synthetic organic sources (readily available and controlled-release) applied at the 100 kg N ha^{-1} application rate experienced significant N leaching losses, but also had the highest N recovery rate in the tissue (Fig. 4B). The higher solubility of the readily available and controlled-release nitrogen sources allowed these sources to be more readily available for uptake, as well as more easily leached. The dairy and swine composts (at 100 kg N ha^{-1}) treatments had the highest P-leaching losses (Table 8), probably a result of excess P application. Clearly tissue recovery of nutrients can influence leaching losses. During establishment, when little turfgrass cover was in place, clipping recovery of N and P was relatively low, despite high tissue nutrient levels. As turf growth and density increased, so did nutrient recovery in the clippings, despite an actual tissue nutrient content decrease. Gaudreau et al. (2002) found that use of manure generally resulted in lower P recovery in the clippings because of more complex P forms, which appear to be less available for plant use, as was likely the case for the low recovery rate of both N and P for the dairy compost at 50 kg N ha^{-1}. The source by time interaction indicates that fertilizer does increase both the clipping dry weight and the total nutrient recovery.

There were large differences in the P and N recovered as a percentage of the amount applied as a function of fertilizer source (Fig. 4). It is likely that the higher

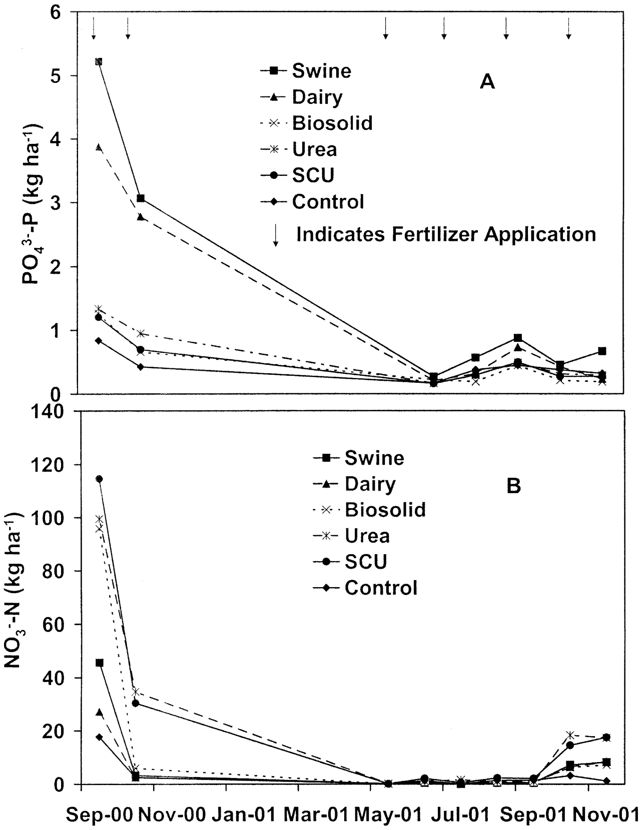

Fig. 5. Phosphate (A) and nitrate (B) mass losses in leachate from turfgrass as a function of fertilizer source over time.

solubility of the N in the synthetic organic sources allowed for greater uptake than the natural organics (Brown et al., 1977), but also allowed greater leaching losses. Despite the higher P application rate with the natural organic sources, very little of the applied P was recovered in clippings, runoff, or leachate. This suggests that much of the applied P remains in the soil, roots, and/or plant tissue.

Long-term repeated use of natural organic sources could result in massive amounts of P and N being stored in the soil, eventually being released and subject to runoff and leaching losses.

CONCLUSIONS

While concentrations of NO_3^-–N in runoff and leachate decreased with time, the levels seen in this study could be problematic for aquatic organisms. Mallin and Wheeler (2000) state that NO_3^-–N levels as low as 0.1 mg L^{-1} can cause eutrophication. In the temperate northeast, PO_4^{3-}–P concentration in excess of 0.024 mg L^{-1} are favorable for eutrophication (Owens et al., 1998). This suggests that the use of aquatic toxicities may be a better indicator of water quality problems (Baird et al., 2000) than human-based maximum contaminant levels. Fertilization on moderately steep slopes in this study represents a scenario that favors nutrient runoff. However, since there are often buffer zones placed between fertilized turf and surface water, dilution and further remediation would probably occur before runoff with these nutrient concentrations would reach water supplies. Leachate was collected directly beneath the root zone, so further plant uptake is not likely to occur, but microbial degradation and soil binding may occur. However, nutrients like NO_3^-–N and NH_4^+–N are ultimately mobile and could move into ground water.

We observed that fertilizers with higher P content had higher P losses, a higher percent of applied P lost, and higher P concentrations. The synthetic-organic fertilizers produced higher NO_3^-–N concentrations and fluxes. Clearly, fertilization during establishment poses the most serious threat to water quality. Not only are concentrations in runoff and leachate higher, but there is generally a higher amount of runoff and greater mass losses as well. It is generally accepted that fertilizer is needed for rapid turfgrass establishment and growth. Increased shoot density, infiltration, and reduced sediment and runoff loss support the argument that fertilization ultimately results in less water contamination. While the initial concentrations and losses were generally higher from the fertilized treatments, rapid establishment and dense growth obtained with fertilizer application tended to reduce overall losses. In many cases we observed equal or higher overall losses of N and P in runoff and leachate from the unfertilized control, supporting the argument that following establishment fertilization can reduce water contamination from N and P. Longer studies need to be conducted to determine the long-term effect of fertilization on water quality.

Table 8. Time by treatment (fertilizer source and rate of application) interaction effects shown for mean nitrate, phosphate, and ammonium mass losses in leachate from turfgrass during establishment (Year 1, July–December 2000) and post-establishment (Year 2, January 2001–January 2002).

Source†	Rate‡	Year	*n*	NO_3^-–N	PO_4^{3-}–P	NH_4^+–N
	kg N ha^{-1}				kg ha^{-1}	
Swine compost	50	1	6	49.0	6.0	6.1
Swine compost	50	2	21	6.1	2.1	4.0
Swine compost	100	1	6	48.7	10.6	4.8
Swine compost	100	2	21	11.7	2.9	2.0
Dairy compost	50	1	6	15.5	3.3	4.6
Dairy compost	50	2	21	4.5	2.0	7.8
Dairy compost	100	1	6	44.0	10.0	5.0
Dairy compost	100	2	21	13.4	3.3	5.8
Biosolid	50	1	6	93.3	2.0	10.7
Biosolid	50	2	21	6.4	1.5	1.5
Biosolid	100	1	6	132.3	1.9	11.7
Biosolid	100	2	21	11.0	1.5	4.0
Readily available	50	1	6	81.8	2.3	10.7
Readily available	50	2	21	18.2	1.3	4.2
Readily available	100	1	6	186.5	2.2	10.7
Readily available	100	2	21	22.0	2.0	1.5
Controlled-release	50	1	6	108.1	2.1	13.5
Controlled-release	50	2	21	17.3	1.6	1.8
Controlled-release	100	1	6	181.7	1.7	8.5
Controlled-release	100	2	21	21.4	2.3	2.2
Control	0	1	8	20.2	1.3	5.6
Control	0	2	28	3.7	1.3	2.4
Fisher's LSD§				21.4	2.1	2.4

† All treatments except the control received a total of 200 kg N ha^{-1} yr^{-1}.
‡ Single fertilizer application rate.
§ Treatments are significantly different if the difference between column means is greater than Fisher's protected LSD at $\alpha \leq 0.05$.

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