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Reducing nitrate leaching losses from turfgrass fertilization of residential lawns

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Abstract

Fertilizer applications on lawns have raised environmental concerns in many Canadian municipalities. In this greenhouse study, NO_3–N leaching losses from Kentucky bluegrass (*Poa pratensis* L.) lawns were evaluated on two soils (a schist loam and a clay loam) and on a sand/peat moss rootzone mix (80% sand, 20% peat moss). Eight different fertilizer N sources (urea, Polyon 8 and 12-wk release, Duration 45 and 90-d release, XCU, corn gluten meal, and UFLEXX) were assessed at five application rates (25–200 kg N ha^{-1} yr^{-1}) and two application frequencies over two 8-wk trials. Average NO_3–N concentration in leachate were measured at levels of 3.5, 7.4, and 1.4 mg L^{-1} from turf grown in loam, clay, and sand respectively, but losses from loam and clay were mostly affected by N mineralization from organic matter. Turf fertilized with rates ≥100 kg N ha^{-1} generally resulted in acceptable visual quality on both soils, but coated-urea fertilizers were more efficient to reduce leaching. In sand, UFLEXX and urea (150 and 200 kg N ha^{-1}) as well as XCU (200 kg N ha^{-1}) resulted in higher NO_3–N losses, varying from 8.5 to 23.7 mg L^{-1}, and losses from other N sources were consistently below 3 mg L^{-1}. Our results show that it is possible to maintain good quality turfgrass while keeping low NO_3–N leaching losses (i.e., <4 mg L^{-1}) in loam, clay, and sand by selecting the ideal combination of N source, N rate, and application frequency.

1 | INTRODUCTION

Turfgrass plays an important role in urban and residential landscapes, providing many benefits (Beard & Green, 1994). However, in recent years, there have been increasing concerns about the negative impacts of turfgrass N fertilization on air and water quality. Recent experiments have shown that polymer-coated urea (PCU) and stabilized urea fertilizers can mitigate these negative impacts compared with urea in turfgrass systems (Barton et al., 2006; Bierman et al., 2010; Carey et al., 2012; Curtis et al., 2020; LeMonte et al., 2016).

Different factors affect N losses through leaching, soil texture (Guertal et al., 2012), N source (Guillard & Kopp, 2004; Mancino & Troll, 1990; Saha & Trenholm, 2007), and fertilizer application rate (including frequency and timing) (Easton & Petrovic, 2004; Mangiafico & Guillard, 2006; Wu et al., 2010). Nevertheless, when good fertilization practices are implemented, nitrate (NO_3–N) losses through leaching are generally low (<10% of the applied N), with NO_3–N concentrations in leachate generally remaining <10 mg L^{-1} (Engelsjord & Singh, 1997; Frank et al., 2016; Guertal & Howe,

Abbreviations: CGM, corn gluten meal; PCU, polymer-coated urea; SCU, sulfur-coated urea; UF, ureaformaldehyde.

2012; Guillard & Kopp, 2004; Petrovic, 1990; Wu et al., 2010).

Several studies have shown that NO_3–N leaching can be mitigated by using polymer-coated urea (PCU) or sulfur-coated urea (SCU). In an experiment on Kentucky bluegrass (*Poa pratensis* L.), Geron et al. (1993) found that NO_3–N losses from plots fertilized with PCU were 43% lower than those of plots fertilized with urea. Engelsjord and Singh (1997) reported that the NO_3–N concentration in leachate from plots fertilized with ammonium nitrate (NH_4NO_3) could seasonally exceed that of plots fertilized with SCU by more than sixfold (see also Wu et al., 2010). In another study, the average annual NO_3–N leaching losses from plots fertilized with polymer- and sulfur-coated urea (PCSCU) were found to be only 10% of those from plots fertilized with NH_4NO_3 (Guillard & Kopp, 2004).

Another fertilizer technology considered to mitigate NO_3–N losses uses urease and nitrification inhibitors (stabilized urea) to slow down urea release. Although the use of N-(n-butyl) thiophosphoric triamide has been shown to enhance N use efficiency by delaying urea hydrolysis in laboratory or field conditions (Dawar et al., 2011; Henning et al., 2013; Mariano et al., 2019), this technology has not necessarily resulted in reduced N leaching losses from turf. One study evaluating the impact of stabilized urea (UMAXX, Ferti Technologies, Inc.) on leaching losses reported a significant 15% reduction of the NO_3–N leached compared with urea but also an increase in NO_3–N leaching compared with PCU (Polyon, Ferti Technologies, Inc.) (Guertal & Howe, 2012).

Several studies have shown that nitrate-N losses through leaching are significantly affected by the applied fertilizer rate. In a study on golf greens, nitrate-N concentration in leachate measured 11 wk after treatment with PCU and SCU applied at four rates (0, 12, 24, and 49 kg N ha^{-1} in six applications) was similar between 0 and 24 kg N ha^{-1} but increased significantly (over sixfold) at a rate of 49 kg N ha^{-1} (Shuman, 2001). Similarly, NO_3–N concentrations in leachate were found to be over four times higher when applying urea at a rate of 245 kg N ha^{-1} yr^{-1} compared with 98 kg N ha^{-1} yr^{-1} (Frank et al., 2006). Using both synthetic fertilizers and organic N sources, Easton and Petrovic (2004) found that doubling the application rate from 50 to 100 kg N ha^{-1} (for a total of 200 kg N ha^{-1} yr^{-1}) increased N–NO_3 losses by 1.5–3 times. Wu et al. (2010) found that fertilizing turf on a sandy loam with NH_4NO_3 at a rate of 293 or 195 kg N ha^{-1} reduced NO_3–N losses in leachate compared with a rate of 390 kg N ha^{-1}.

Splitting the required N rate into several applications also influences nitrate-N leaching losses. For example, Mancino et al. (1990) measured leaching N losses from turf grown on sand and fertilized with NH_4NO_3 or calcium nitrate applied at a rate of either 10 kg N ha^{-1} every week or 20 kg N ha^{-1} every 14 d (annual rate of 98 kg N ha^{-1}). Although they did not observe significant differences in total leaching losses, over four times less NO_3–N was leached from these treatments compared with a single application of NH_4NO_3 or calcium nitrate at a rate of 48 kg N ha^{-1}. In contrast, Engelsjord and Singh (1997) found similar amounts of N leached (<3% of N applied) from turf fertilized with either a single application of SCU or a biweekly application of a soluble fertilizer. These studies show that, although quick-release fertilizers are generally more subject to N losses through leaching, this N loss risk can be mitigated by adequately managing the N application rate and its pattern over time.

Core Ideas

- Low NO_3–N leaching losses (<4 mg L^{-1}) were found in loam, clay, and sand.
- Stabilized urea and polymer/sulfur coated urea failed to mitigate nitrate-N leaching in sand.
- Rates >150 kg N ha^{-1} should be avoided to reduce leaching from residential turf.
- Organic N mineralization contributes to leaching losses during turfgrass establishment.
- It is possible to maintain good quality turfgrass while keeping low NO_3–N leaching losses.

Soil texture also significantly affects water infiltration and thus leachate N concentrations (Petrovic, 1990). Generally, N leaching losses are greater on sandy soils (Barton & Colmer, 2006), yet little research has focused on leaching losses from turfgrass grown on fine-textured soils. In a study conducted on golf putting greens, two different sand/clay mixes (5 and 10% clay content) have been shown to reduce NO_3–N losses through leaching by 35% compared with a sand putting green (Brown et al., 1982). In another study, NO_3–N concentration in leachate from a sandy loam (70.7% sand, 19.8% silt, 11.3% clay) was found to be 3% lower than from a loamy sand (84% sand, 9.8% silt, 7.7% clay) during the first season (Wu et al., 2007). Although fine-textured soils may reduce leaching losses by increasing water retention in soil, they can also increase N losses under specific conditions because of their potentially higher organic matter content. Indeed, Guertal and Howe (2012) reported nitrate leaching losses as high as 103.6 mg NO_3–N L^{-1} in the 70-d period following turfgrass establishment on a clay soil and attributed these losses to rapid organic matter N mineralization following soil disturbance. In contrast, NO_3–N leaching losses from turfgrass established on a sandy loam or a loamy sand were <10 mg L^{-1} during the same period.

Although several studies have evaluated the impact of different factors (N application rate, N source, and application frequency) on nitrate losses through leaching, few have

TABLE 1 Initial soil chemical analysis and organic matter content for each soil type

Soil type	CEC	OM	NO_3–N	P	K	Ca	Mg	Fe
	$cmol_c$ kg^{-1}	%	mg kg^{-1}					
Sand/peat moss	6.6	0.7	0	7	3	97	17	54
Schist loam	8.2	5.4	0.5	61	61	516	51	258
Clay loam	24.4	4.8	4.7	114	184	3219	55	342

Note. CEC, cation exchange capacity; OM, organic matter.

attempted to evaluate the combined effects of those factors in different soil textures. In this context, the objective of this study was to determine the combinations of N rate, N source, and application frequency resulting in the lowest N leaching losses from turfgrass grown in three different soil textures (sand, loam, and clay) while maintaining an acceptable turfgrass quality.

2 | MATERIALS AND METHODS

2.1 | Experimental design

A greenhouse experiment was initiated in February 2019 at the Centre de Recherche et d'Innovation sur les Végétaux at Université Laval in Quebec City, Canada. Three series of two trials were conducted from 27 February to 1 June, from 18 June to 16 September, and from 25 September to 22 December, for a total of six trials. Those included two repetitions on each of the following soils or growing substrates (Supplemental Table S1): a sand-based rootzone mix (80% sand, 20% peat moss), a schist loam (58% sand, 25% silt, 17% clay, orthic ferro-humic podzol, St-Nicolas series), and a clay loam (26% sand, 45% silt, 29% clay, orthic ferro-humic podzol, Tilly series) (Canadian Agricultural Services Coordinating Committee, 1998; Laplante, 1962; Raymond et al., 1976). The sand mix was obtained from a local distributor (Les Matériaux paysagers Savaria), and the loam and clay were collected from local fields. The Mehlich-3 extraction procedure (Mehlich, 1984) and atomic absorption spectrometry (Wright & Stuczynski, 1996) were used for soil P, K, Ca, Mg, and Fe content analysis (Table 1); cation exchange capacity was calculated from Melich-3 results. Organic matter content was estimated with the loss-on-ignition method (Centre d'expertise en analyse environnementale, 2003), and KCl extraction was used for soil initial nitrate-N content analysis (Maynard et al., 1993).

Turf was grown in modified mini-treepots (10.2 cm by 10.2 cm by 24.1 cm; TP49CH mini-forestry pots, Stuewe & Sons, Inc.). A perforated clear plastic bag was first placed in each pot to allow drainage from the center bottom hole but not from the sidewall holes. A 1.27-cm-diameter male electrical box PVC adapter (TA07, Kraloy) was then placed through the liner and the drainage hole and kept in place using a 1.27-cm-diameter steel locknut (KILLN2, Hubbell Inc.). A piece of garden fabric (20 cm by 20 cm; Agryl-P12 12 g m^{-2}, Dubois Agrinovation) was placed on top of the hole and used as a filter cloth. Pots were then filled with soil, irrigated to promote soil settling, and refilled with soil to a height of ∼1 cm from the top of the pot. Kentucky bluegrass (*P. pratensis* 'Bedazzled') was hand seeded in pots at a rate of 1.27 kg 100 m^{-2} and seeds were covered with a 1 mm layer of sphagnum peat moss (Pro-mix BX mycorrhizae, Pro-Mix, Premier Tech). After 14 d, each pot received 5 mg of N, 2 mg of P_2O_5, and 5 mg of K_2O from a 20–8–20 fertilizer solution (10561 High nitrate fertilizer, Master Plant-Prod Inc.). Diurnal air temperature in the greenhouse was kept at 22 ˚C, and nocturnal temperature was set at 18 ˚C. Relative humidity was maintained at 60% except during seed germination, during which it was set at 80% and vertical shades were lowered. By Week 5, turfgrass coverage was visually estimated to be 100% for most of the pots (Supplemental Figure S2). During the second series of trials, three applications of microscopic sulfur 92% (Loveland Products Canada, Inc.) were made on all pots to prevent the development of powdery mildew (*Erysiphe graminis*). A sulfur lamp (YASSA, Groupe Horticole Ledoux) was installed in the greenhouse for the third series. Turfgrass was mowed twice per week at a height of ∼6 cm from the soil using a battery-powered garden shear (HAS 25, STIHL).

2.2 | Fertilizer treatments

Each trial was arranged as a completely randomized block design with four replicates. Three factors were evaluated in this experiment: eight N sources, five application rates, and two application frequencies (80 treatments in total). Four unfertilized control pots were added to each block, for a total of 336 experimental units. Eight fertilizers sources (urea, Polyon 8 and 12-wk release, Duration 45 and 90-d release, XCU, corn gluten meal [CGM], and UFLEXX) (Ferti Technologies Inc.) applied at five N rates (25, 50, 100, 150, and 200 kg N ha^{-1} yr^{-1}) and two frequencies (a single application and two half-rate applications) were evaluated. The first fertilizer application was made 21 d after seeding (Week 0), and the second fertilizer application (for the treatments requiring two applications) was made on Week 4. Fertilizations were made on 1 and 30 April (Trial 1) and on 15 July and 12 August (Trial 3) in loam, on 26 March and 24 April (Trial 2) and on 22 October and 18 November (Trial 6) in sand, and on 16 July and 13 August (Trial 4) and 22 October and 18 November (Trial 5) in clay (Supplemental Table S1).

2.3 | Leachate collection and analysis

Turf was irrigated weekly to induce leaching, including once before the first fertilizer application as a Time 0 sample. A drip system, using perforated plastic cups, was used to slowly deliver water to each pot (350 ml pot^{-1} in loam and 250 pot^{-1} in sand and clay), thus preventing preferential flow through the edge of the pots. This water quantity corresponds to the lower end of local recommendations for weekly lawn irrigation (Charbonneau, 2014) and was sufficient to induce leaching from most pots without exceeding the collection tube volume. Because water losses through evaporation varies from one pot to another (Huang & Petrovic, 1994; Krofft et al., 2020), we added an additional 50 ml of water after 10 min to the few pots from which leaching had not been triggered from the initial water application in order to collect samples from all experimental units. Leachate accumulated into 50-ml sterile polypropylene centrifuge tubes (VWR, Radnor) fixed to the bottom of each pot. Samples were collected from these tubes, transferred into a 2-ml polypropylene plastic tube (Simport Scientific), and stored at 4 ˚C for up to 30 d. Leachate content in NO_3–N was determined by the second-derivative visible spectroscopy technique for nitrate (Ferree & Shannon, 2001) using a Epoch 2 Microplate Spectrophotometer (BioTek Instruments Inc.), and NH_4–N content was determined using a colorimetric procedure for N determination in micro-Kjeldahl digests based on the Berthelot reaction (Nkonge & Balance, 1982). Detection limits were 0.6 mg L^{-1} for NO_3–N and 0.4 mg L^{-1} for NH_4–N. Visual quality evaluations, on a 1–9 scale (1 = brown and dead turf, 9 = optimum turf, and 6 = minimally acceptable turf for use in home lawns), were performed once per week for 8 wk during each trial.

2.4 | Statistical analysis

Data from this experiment were analyzed using two separate models, which were applied to each growing substrate type. Concentrations of NO_3–N were first analyzed using two-way repeated-measures ANOVA estimated with a linear mixed model to compare the control treatment with the other treatments either on a weekly basis or for the entire experiment. Random effects were considered for trials, blocks, and pots, including a first-order autoregressive covariance structure for repeated measures over weeks. Dunnett-adjusted multiple comparisons were used on NO_3–N concentration means estimations. The second model, which excluded data from the unfertilized control, used a four-way repeated-measures ANOVA with a linear mixed model to measure the effect of fertilizer sources, N rates, number of applications, and time (weeks). Tukey's HSD test was used as a post hoc test for comparison of NO_3–N concentration means estimations. Statistical analysis was conducted using lme, anova, and emmeans functions from the 'nlme', 'stats', and 'emmeans' packages, respectively, in R Studio version 1.1.46 (RStudio, 2019).

TABLE 2 Summary of ANOVA effects of N source, rates, and number of applications on NO_3–N leaching losses for each growing substrate

	p value		
Source of variation	**Sand**	**Loam**	**Clay**
Source (S)	<.0001	NS	<.0001
Rate (R)	<.0001	NS	<.0001
Application (A)	<.0001	NS	0.0017
Week (T)	<.0001	<.0001	<.0001
S × R	<.0001	NS	NS
S × A	<.0001	NS	NS
R × A	<.0001	NS	NS
S × T	<.0001	.0125	.0008
R × T	<.0001	.0087	<.0001
A × T	<.0001	.0021	.0271
S × R × A	NS	NS	NS
S × R × T	<.0001	NS	NS
S × A × T	<.0001	NS	NS
R × A × T	<.0001	NS	NS
S × R × A × T	<.0001	NS	NS

Note. NS, not significant.

3 | RESULTS

3.1 | Factors affecting nitrate leaching losses

Leaching losses were initially high in loam and clay, even before the first fertilization (Supplemental Figure S3). Using data from all sampling weeks and treatments, average NO_3–N leaching was measured at levels of 3.5, 7.4, and 1.4 mg L^{-1}, respectively, in loam, clay, and sand. Factors affecting NO_3–N losses for each of the three growing substrates are presented in Table 2.

3.1.1 | Effect of N rate on leaching losses

Average NO_3–N losses in leachate from the unfertilized control in loam, clay, and sand during the trials were measured, respectively, at levels of 3.3, 5.9, and 0.6 mg NO_3–N L^{-1}. Fertilizing turfgrass with any treatment did not result in a significant increase in NO_3–N leaching losses in loam compared with the unfertilized control (Supplemental Figure S4). In clay, the 200 kg N ha^{-1} rate resulted in leaching losses significantly higher than the unfertilized control (Figure 1a), especially when urea or UFLEXX were applied. In sand, applying

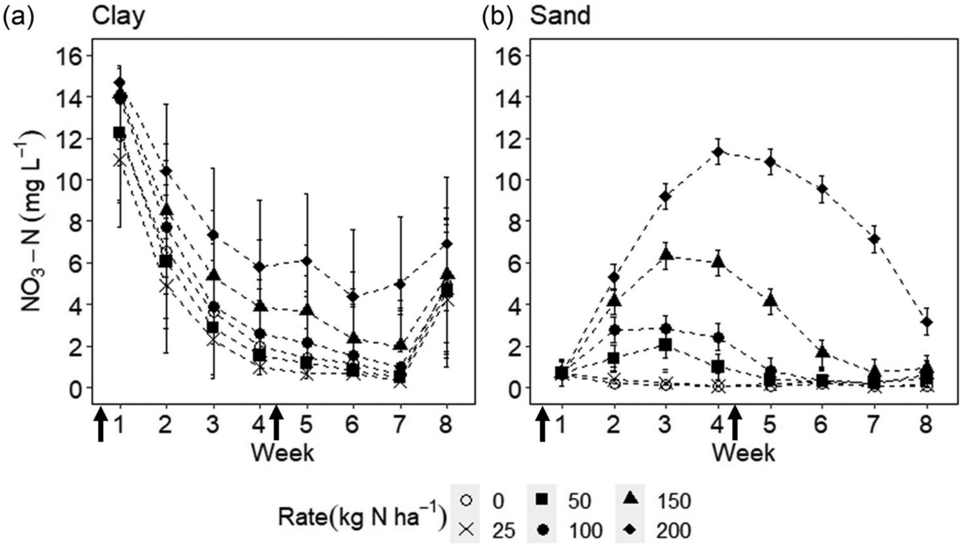

FIGURE 1 Effect of N rates on NO_3–N losses in leaching over 8 wk from (a) clay and (b) sand. Means are averaged over the levels of N sources and application frequency and across the two trials. Error bars represent SE. Vertical arrows indicate the first and second N applications, which occurred after leaching at Week 0 for all treatments and Week 4 for half of the treatments (see Materials and Methods section for details)

N at rates of 100, 150, and 200 kg N ha^{-1} resulted in significantly higher NO_3–N leaching losses compared with the unfertilized control from Weeks 2 to 5 (Figure 1b), although these differences were not attributable to all N sources and application frequencies.

Mean NO_3–N concentrations were detected at a significantly higher level of 9.8 mg L^{-1} with the rate of 200 kg N ha^{-1} compared with 5.8, 6.5, and 7.3 mg L^{-1} measured, respectively, from the rates of 25, 50, and 100 kg N ha^{-1} in clay, whereas the N rate main effect did not affect mean NO_3–N losses in loam (Supplemental Figure S4). Moreover, mean NO_3–N concentrations measured in leachate were significantly lower when N rates of 25, 50, and 100 kg N ha^{-1} were used compared with the 200 kg N ha^{-1} rate from Weeks 2 to 5 in loam and from Weeks 3 to 7 in clay (Figure 1a).

Mean NO_3–N concentrations in leachate were minimal (<2 mg L^{-1}) under N rates of 25, 50, and 100 kg N ha^{-1} in sand, whereas applying 150 kg N ha^{-1} significantly increased NO_3–N leaching losses to an average level of 3.2 mg L^{-1}. These losses more than doubled (6.9 mg L^{-1}) under the 200 kg N ha^{-1} rate (Figure 1b). Moderate NO_3–N losses (5 mg L^{-1}) were detected at each sampling week, but rates of 150 and 200 kg N ha^{-1} resulted in significantly higher losses (up to 6.3 and 11.3 mg NO_3–N L^{-1}, respectively) in Weeks 3 and 4 (Figure 1b).

3.1.2 | Effect of N source on leaching losses

Two weeks after the first fertilizer application in loam, using stabilized urea (UFLEXX) resulted in significantly higher mean NO_3–N leaching losses (3.9 mg L^{-1}) than Polyon 12 and Polyon 8 fertilizers (<1.5 mg L^{-1}) (Supplemental Figure S5). Applying Polyon 12 or Duration 90 resulted in significantly lower NO_3–N leaching losses (<5 and <3 mg L^{-1} in Weeks 2 and 3) than UFLEXX (10.3 and 6.2 mg L^{-1}) in clay. Moreover, losses from urea were detected at a high level (10.9 mg L^{-1}) in the second week after the first fertilizer application, and thereafter these remained over twice as high as those recorded on plots fertilized with PCU. However, from Week 5, NO_3–N leaching losses from both soil types decreased over time irrespective of N source.

In sand, three N sources (UFLEXX, urea, and XCU) resulted in significantly higher NO_3–N losses than all other N sources during Weeks 2–5 (and beyond Week 5 in the case of UFLEXX and urea) (Figure 2b). During those weeks, mean NO_3–N losses measured from turf fertilized with urea and UFLEXX were consistently twice as high as those measured from turf fertilized with XCU (Figure 2b). Mean NO_3–N losses from these three N sources decreased from Week 4 onward, ending at <2 mg L^{-1} after 8 wk for XCU in comparison to 3.3 and 3.2 mg L^{-1}, respectively, for UFLEXX and urea (Figure 2b).

Nitrate-N leaching losses in sand were also affected by the source × rate × application and time interaction effect. Without the effects of time and application frequency, mean NO_3–N leaching losses were significantly higher under the rates of 150 and 200 kg N ha^{-1}, respectively, with UFLEXX (9.9 and 15.8 mg L^{-1}), urea (8.9 and 23.7 mg L^{-1}), and under the highest rate with XCU (8.5 mg L^{-1}) (Supplemental Figure S6). The NO_3–N leachate concentration from all other combinations of N source and rate remained significantly lower (5 mg L^{-1}). Nitrate-N leaching losses exceeded 10 mg L^{-1} following fertilization with UFLEXX and urea applied

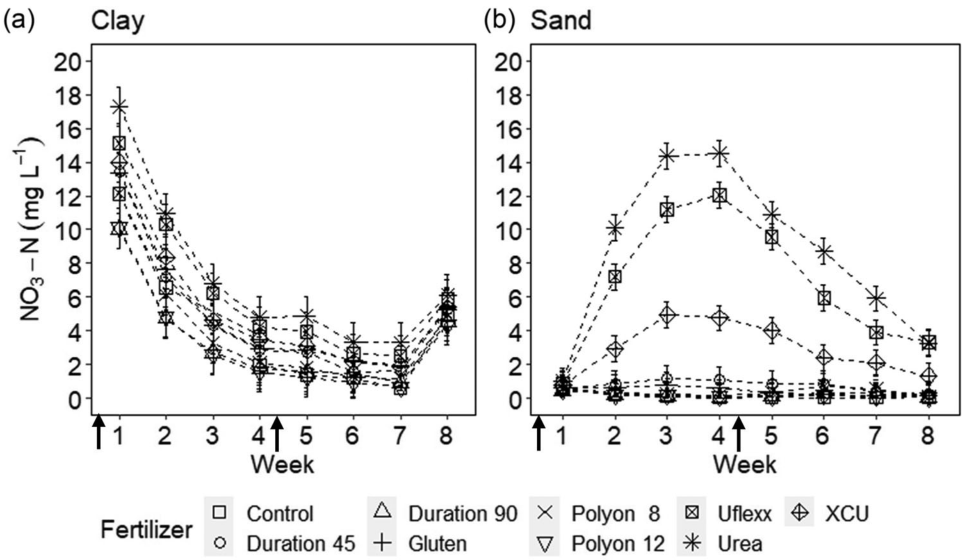

FIGURE 2 Effect of N sources on NO_3–N losses in leaching over 8 wk from (a) clay and (b) sand. Means are averaged over the levels of N rates and application frequency and across the two trials. Error bars represent SE. Vertical arrows indicate the first and second N applications, which occurred after leaching at Week 0 for all treatments and Week 4 for half of the treatments (see Materials and Methods section for details)

either at 150 (Weeks 2–5) or 200 kg N ha^{-1} (Weeks 2–8) (Supplemental Figure S7). Moreover, maximum levels of NO_3–N losses (observed under the 200 kg N ha^{-1} application rate) were measured on Week 5 with UFLEXX (27.3 mg L^{-1}) and on Week 6 with urea (40.3 mg L^{-1}). Split applications of UFLEXX, urea, and XCU at rates of 100, 150, or 200 kg N ha^{-1} significantly reduced NO_3–N losses but did not affect the other combinations of N source and rate.

3.1.3 | Effect of the application frequency on leaching losses

Application frequency significantly affected average NO_3–N losses in each growing substrate. In loam, lower NO_3–N losses were measured during Weeks 1–4 from treatments receiving split N applications, which allowed a 33% reduction in the cumulative NO_3–N losses compared with the one N application treatment (although the main effect of this factor was not significant). Mean NO_3–N concentrations were reduced by 20% in clay for treatments receiving two applications of N, with differences from the single-application treatments being significant only from Weeks 1 to 5. In sand, mean NO_3–N losses from turf receiving a single N application (3.83 mg L^{-1}) were over twice higher than those obtained with the two-applications treatments (1.66 mg L^{-1}), the differences being notable mostly from Weeks 1 to 6.

3.2 | Factors affecting turf visual quality

Turfgrass visual quality was significantly affected by each of the individual fixed factors (N source, N rate, and N application frequency) in sand and loam and by interactions between most of those factors (with exceptions for the rate × application and source × rate × application interactions). In clay, turf quality was significantly influenced by the N source and rate main factors and the source × rate and source × application interactions. Moreover, a significant interaction between each of the three main factors with time was detected in all three growing substrates.

3.2.1 | Effect of N rate on visual quality

Average turf visual quality from the unfertilized control in the three growing substrates was consistently below the acceptable threshold level (i.e., <6.0). Applying lower N rates (25 and 50 kg N ha^{-1}) occasionally resulted in similar turf visual quality than the unfertilized treatments in loam and clay. Acceptable to good turf quality was generally observed for all N application rates over the 8-wk period (except for 25 kg N ha^{-1}) regardless of the N source and application frequency (Table 3). Nitrogen application rates of 100, 150, and 200 kg N ha^{-1} resulted in good quality turf (>6.5 in clay and >7 in loam) on most sampling weeks. In sand, mean turf visual

TABLE 3 Weekly turf visual quality scores in relation to N application rate for the three growing substrates

	Week							
N rate	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Cumulative mean**
kg ha^{-1}								
Loam								
25	6.5	6.1	6.2	5.7a	5.8a	5.9a	6.1a	6.1
50	6.8	6.5	6.5	6.2b	6.3b	6.4b	6.6b	6.5
100	7.1	6.9	7.1	6.9c	7.0c	7.2c	7.3c	7.1
150	7.3	7.2	7.4	7.3d	7.5de	7.6d	7.7d	7.4
200	7.3	7.4	7.6	7.5e	7.7e	7.8e	7.8e	7.6
Clay								
25	6.1	5.8	5.9	6.1a	5.9a	5.9a	5.8a	5.9
50	6.3	6.0	6.2	6.3a	6.2b	6.3b	6.2b	6.2
100	6.4	6.2	6.7	6.8bc	6.8c	7.0cd	6.9cd	6.7
150	6.4	6.3	6.9	7.0c	7.0c	7.2d	7.0d	6.8
200	6.3	6.2	6.8	6.9c	7.0c	7.3d	7.2d	6.8
Sand								
25	5.3	4.9	4.9	4.9a	4.9a	5.0a	4.9a	5.0
50	5.7	5.4	5.4	5.4b	5.7b	6.0b	5.7b	5.6
100	6.1	6.0	6.1	6.0c	6.3c	6.5c	6.3c	6.2
150	6.1	6.0	6.3	6.3c	6.5c	6.9d	6.6cd	6.4
200	6.0	6.0	6.4	6.3c	6.5c	6.9d	6.8d	6.4

Note. Data followed by the same letters are not significantly different. Contrasts results obtained by the Tukey's test ($\alpha = .05$) are presented only for Weeks 5–8 to lighten the information. Starting from Week 5, fractioned treatments had received the second N application, which allowed us to evaluate the direct effect of the N application rate.

quality scores were rated at 6.2, 6.4, and 6.4 under the rates of 100, 150, and 200 kg N ha^{-1}, respectively (Table 3). Foliar discoloration was sometimes observed for UFLEXX and urea at high rates and had an adverse effect on turf visual quality.

3.2.2 | Effect of N source on visual quality

Four N sources (Duration 45, CGM, urea, and XCU) resulted in mean turf visual quality scores higher than 7 in loam, although turf fertilized with CGM did not achieve this visual quality level until the end of the experiment (Table 4). Moreover, turf fertilized with Polyon 12 showed significantly lower mean visual quality compared with all other N sources (except for Duration 90) during Weeks 3–6, although we observed acceptable visual quality under the 150 or 200 kg N ha^{-1} rates. In clay, average scores measured from turf fertilized with CGM, Duration 45, Polyon 8, and XCU were significantly higher (>6.5) than for all other N sources (with the exception of urea compared with Polyon 8) (Table 4). Turf fertilized with CGM resulted in significantly higher visual quality compared with all other N sources during the first 6 wk in sand (Table 4). Applying Polyon 12 resulted in the lowest mean scores for turf visual quality among all N sources (6.1 and 5.3, respectively, in clay and sand).

3.2.3 | Effect of application frequency on visual quality

In sand and loam, turf visual quality was generally higher when N was supplied as a single application compared with the split application approach, although this was mostly true before the second application was made. For example, Duration 45 and Polyon 8 applied at rates ≥100 kg N ha^{-1} in a single application resulted in significantly higher turf visual quality compared with other N sources in sand. In clay, application frequency did not influence the overall turf quality, but a single N application resulted in significantly higher turf visual quality compared with the split N treatments during Weeks 4 and 5.

4 | DISCUSSION

4.1 | Sand

Different combinations of N sources, N rates, and application frequencies induced a variable response in NO_3–N leaching from sand over time. Mean NO_3–N losses across all treatments and sampling weeks was lower (1.4 mg L^{-1}) than expected (∼4 mg L^{-1}) knowing the poor retention

TABLE 4 Weekly turf visual quality scores in relation to N source for the three growing substrates

N source	Week							Cumulative mean
	2	3	4	5	6	7	8	
Loam								
CGM[a]	7.4	7.1	7.0	6.8bc	7.0bc	6.9a	6.9a	7.0
Duration 45	7.2	6.9	7.0	6.8c	7.0bc	6.9a	7.3b	7.0
Duration 90	6.5	6.4	6.8	6.5b	6.8b	7.0ab	7.2b	6.7
Polyon 12	6.3	6.2	6.4	6.1a	6.5a	6.7a	7.0ab	6.5
Polyon 8	6.9	6.7	6.9	6.8bc	7.0bc	7.1ab	7.3c	7.0
UFLEXX	7.0	6.9	7.0	6.7bc	6.9b	6.9a	6.9a	6.9
Urea	7.5	7.2	7.3	6.9c	7.1c	7.1ab	7.1ab	7.2
XCU	7.4	7.1	7.2	6.9c	7.0bc	7.1ab	7.1ab	7.1
Clay								
CGM	6.8	6.4	6.8	7.0c	6.8c	6.9b	6.7ab	6.8
Duration 45	6.6	6.4	6.7	6.9c	6.8c	6.9b	6.7ab	6.7
Duration 90	6.0	5.9	6.2	6.5ab	6.5abc	6.6ab	6.6ab	6.3
Polyon 12	6.0	5.7	6.0	6.2a	6.2a	6.3a	6.4a	6.1
Polyon 8	6.4	6.2	6.5	6.7bc	6.7bc	6.8b	6.8ab	6.6
UFLEXX	6.0	5.7	6.4	6.4ab	6.3ab	6.6ab	6.4a	6.3
Urea	6.3	6.1	6.5	6.5ab	6.6abc	6.7b	6.5ab	6.4
XCU	6.6	6.5	6.7	6.9c	6.8c	7.0b	6.8b	6.7
Sand								
CGM	6.7	6.5	6.5	6.4c	6.5d	6.7b	6.2a	6.5
Duration 45	6.3	6.0	6.0	5.9b	6.2 cd	6.3ab	6.1a	6.1
Duration 90	5.2	5.1	5.5	5.7b	5.9bc	6.3ab	6.2a	5.7
Polyon 12	4.8	4.7	5.0	5.1a	5.4a	6.0a	5.9a	5.3
Polyon 8	5.8	5.5	5.8	5.8b	6.0bc	6.3ab	6.2a	5.9
UFLEXX	5.5	5.6	5.7	5.7b	5.8ab	6.0a	5.9a	5.8
Urea	6.0	5.9	6.0	5.7b	5.9bc	6.2a	5.9a	6.0
XCU	6.3	6.0	6.1	6.0bc	6.1bc	6.3ab	6.1a	6.1

Note. Data followed by the same letters are not significantly different. Contrasts results obtained by the Tukey's test ($\alpha = .05$) are presented only for Weeks 5–8 to lighten the information. Starting from Week 5, fractioned treatments had received the second N application, which allowed us to evaluate the direct effect of the N source.

[a] Corn gluten meal.

capacities of sand (Barton & Colmer, 2006). This is consistent with previous results from Engelsjord and Singh (1997), who reported average NO_3–N losses of <2 mg L^{-1} for a 2-mo-old turf grown on 80% sand/20% peat moss rootzone. Significant increases in NO_3–N leaching compared with unfertilized plots mostly occurred for UFLEXX, urea, or XCU applied at the 150 and 200 kg N ha^{-1} rates in the present research. Guertal and Howe (2012) also reported greater losses on sandy soil with urea and stabilized urea compared with Polyon and unfertilized turf. In contrast, LeMonte et al. (2016) did not found any significant difference in NO_3 losses between PCU and urea either on a sandy or a loamy soil. In the present experiment, fertilization with UFLEXX did not significantly reduce NO_3–N losses in sand compared with urea, in contrast to results from Guertal and Howe (2012). This could be because nitrogenase inhibitors are highly soluble and sensitive to differential transport mechanisms through the soil macropores (Henning et al., 2013). The high NO_3–N losses (8.5 mg L^{-1}) from PCSCU applied at 200 kg N ha^{-1} in our study were substantially higher than those measured by Guillard and Kopp (2004) under a rate of 147 kg N ha^{-1}. However, because PCSCU resulted in the highest average turf visual quality and losses remained <5 mg L^{-1} 5 wk after the first N application, we suggest that split applications of XCU at the 150 or 200 kg N ha^{-1} rates would pose little risk for N leaching over a longer period. The efficiency of slow-release fertilizers has indeed been repeatedly demonstrated (Easton & Petrovic, 2004; Guertal & Howe 2012; Guillard & Kopp, 2004; Wu et al., 2010); however, our study is the first to report that CGM could mitigate NO_3–N leaching in sand with comparable efficiency (Figure 2). Our results also indicate that visual quality of turf established on sand is mostly affected by the applied N rate, which corroborates previous findings (Badra et al., 2005; Engelsjord & Singh, 1997; Wu et al., 2010). Based on our findings, using PCU or CGM at a rate of ≥100 kg N ha^{-1} should yield high-quality turfgrass while maintaining low NO_3–N leaching losses (<5 mg L^{-1}) in sand.

4.2 | Loam

Nitrate-N leaching losses from turf grown in loam were generally <5 mg L^{-1} across all N sources and application rates (average, 3.5 mg NO_3–N L^{-1}), which is similar to losses reported by Wu et al. (2010). Guertal and Howe (2012) also reported low leachate N concentrations from a loamy sand 14 d after fertilization under an N application although only under a rate of 73 kg N ha^{-1}. In our study, we observed greater NO_3–N losses in leachate mostly under the highest rate of 200 kg N ha^{-1} (Figure 1). However, our results suggest that time after establishment is the main factor affecting NO_3–N leaching in loam because NO_3–N concentration in leachate was high (17.9 mg L^{-1}) before any N application and decreased below 1 mg L^{-1} after 4 wk. A similar decreasing pattern over time was also revealed by Guertal and Howe (2012), who did not detect any difference between all evaluated N sources 35 d after N application under a 73 kg ha^{-1} rate. Because the highest NO_3–N leachate concentration in loam preceded the first fertilization and because none of the treatments resulted in significantly higher losses compared with unfertilized turf, it is likely that N mineralization was the main driver of NO_3–N losses during our experiment. Our results from the loam also indicate that good turf visual quality can be obtained under N rates ≥100 kg N ha^{-1}, but polymer-coated fertilizers should be privileged to reduce NO_3–N.

4.3 | Clay

Nitrate-N losses measured from turf receiving the 50 or the 100 kg N ha^{-1} in clay were about three times higher than those reported by Guertal and Howe (2012) on a 1-yr-old lawn fertilized with 73 kg N ha^{-1} (1.6 mg L^{-1}). Applying lower N rates is expected to reduce nitrate leaching furthermore (Frank et al., 2006; Petrovic, 1990; Wu et al., 2010), and our findings indicate that, on clay, an application rate of 50–100 kg N ha^{-1} is sufficient to obtain an acceptable quality turfgrass. Our results also highlight the importance of using slow-release fertilizers (particularly polymer-coated urea) even in heavy soils. In this regard, stabilized N was not as effective as other slow-release N sources (PCU and natural fertilizer) to reduce NO_3–N losses through leaching in clay (see also Guertal & Howe, 2012). Because only a few studies have attempted to measure leaching from fine-textured soils, our study provides additional information about the N range and N sources, precisely Duration 90 (50–150 kg N ha^{-1}) or Polyon 12 (100–200 kg N ha^{-1}), that should be applied on loam and clay to reduce nitrate leaching while maintaining good turf visual quality. As in previous studies (Geron et al., 1993; Guertal & Howe, 2012), our results support the idea that N mineralization of soil-N promoted by soil disturbance can have a stronger impact on NO_3–N leaching losses than fertilization practices in fine-texture soils.

5 | SUMMARY AND CONCLUSIONS

Results of the present study demonstrate that low NO_3–N leaching losses (i.e., <4 mg L^{-1}) can be achieved in loam, clay, and sand by selecting the ideal combination of N source, N rate and application frequency while maintaining acceptable turf visual quality. Concretely, fertilization programs on residential lawn in Québec and other jurisdictions with similar climate should prioritize polymer coating to slow down the N release from urea and avoid seasonal application rate that exceed 150 kg N ha^{-1}, especially for quick-release N sources. The temporal response of turf relatively to N applications as well as the contribution of soil organic mineralization during turf establishment might also affect leaching losses. In order to possibly reduce threats of NO_3–N leaching under field conditions, the optimal combinations of N source, rate, and application frequency highlighted in this study should be investigated over several years.

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AUTHOR CONTRIBUTIONS

Laura Côté: Formal analysis; Investigation; Methodology; Writing-original draft. Guillaume Grégoire: Conceptualization; Funding acquisition; Methodology; Project administration; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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