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Nitrate and Tracer Leaching from Aerated Turfgrass Profiles

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Summary

Macropore flow has received increased attention in the recent years due to its importance on solute flow through the vadose zone and contamination of groundwater. The effects of man-made macropores resulting from cultivation of turfgrass sites on the mobility of nitrates and tracer chloride were studied. Treatments included two soil profiles (a sandy profile, simulating a US Golf Association style putting green and a sandy clay soil) and three cultivation practices (shallow hollow tines, 80 mm deep and 19 mm internal diameter (I.D.); deep drill, 220 mm deep and 19 mm I.D.; and high pressure water injection). Free draining lysimeters sodded with *Agrostis stolonifera ssp. palustris* Huds. var. 'Providence' were used in greenhouse to perform three studies. In the first study, turfgrass was fertilized with a solution fertilizer at a rate of 24 kg N ha^{-1} and a daily irrigation of 6.8 mm in excess of the predetermined field capacity. In the second greenhouse study the irrigation rate was increased to 13.7 to 27.4 mm d^{-1} simulating an overwatering regime. In the third study turfgrass was fertilized with $(NH_4)_2SO_4$ as nitrogen (N) source at a rate of 49 kg N ha^{-1} and 13 mm of daily irrigation was applied while the plants were sufficient in N. In addition chloride was utilized as a nitrate tracer. In the first study, NO_3 was detected after 2 L of effluent volume from the sand profiles and peaked at 13 to 14 mg NO_3-N L^{-1} at 3 L of effluent volume. Nitrate leaching was not affected by the cultivation treatments. However, at a higher daily irrigation schedule (13.7 to 27.4 mm d^{-1}), NO_3 concentration from the sand profiles reached 18 to 20 mg NO_3-N L^{-1} but the differences between cultivated and uncultivated profiles were less pronounced compared with the low irrigation regime. Nitrate leaching was not detected from the sandy clay profiles for any of the two irrigation regimes due to a large amount of N plant uptake. In the third study, NO_3 leaching from the sandy profiles peaked more rapidly from the shallow and deep cultivated profiles reaching 54 mg NO_3-N L^{-1} for both treatments. Water injected and uncultivated profiles peaked at 45 mg NO_3-N L^{-1}. Chloride analysis suggested that macropore flow through cultivation holes did not affect solute flow past the root zone in the sand profiles. The mass of NO_3-N lost by leaching differed between studies according to the irrigation rates and the level of N sufficiency of the plants. It was concluded that under proper management practices, turfgrass cultivation is not expected to enhance nitrate leaching.

Key words. Core cultivation – deep drill – hydroject – lysimeter – turfgrass cultivation – preferential flow – USGA sandy profile

Introduction

Aquifer contamination from nitrates has been detected in the United States, European Community countries, Africa, New Zealand, Australia, Caribbean and Middle East (Spalding and Exner 1993). Nitrates are considered to be the most widespread contaminant of groundwater reservoirs (Pye et al. 1983). Nitrate contamination can result from leaks in septic tanks, animal and human wastes as well as from leaching of agricultural fertilizers. Flipse et al. (1984) proposed that leaching of turf-applied fertilizers can also be a major source for groundwater contamination in suburban areas. In contrast Cohen et al. (1999) sampled surface and groundwater in the vicinity of golf courses and found that only 3.6% of the groundwater samples exceeded the maximum contaminant level (MCL) which was correlated to prior agricultural use. On surface water the researchers did not detect nitrate-N exceeding the MCL.

However, under certain circumstances NO_3 leaching from turf-applied fertilizers has been shown to exceed the USEPA standard of 10 mg NO_3-N L^{-1} (Snyder et al. 1984;

Liu et al. 1997; Miltner et al. 1996; Guillard and Kopp 2004, Paulino-Paulino et al. 2008). Therefore, it is of major importance to accurately predict and minimize the potential of NO_3 contamination from turfgrass systems. Research has been shown that water, fertilizers and other solutes can move preferentially through the soil and cause contamination of the groundwater much faster than expected (Adreini and Steenhuis 1990; Nektarios et al. 1999, 2004, 2007; Larsbo et al. 2008; Espevig and Aamlid 2012.).

Examples of preferential flow from turfgrass systems are limited but not uncommon. Roth-Borromeo (1992) observed fast movement of pesticides through silt loam profiles that was probably caused by earthworm activity. Morton et al. (1988) noticed a substantial increase in inorganic-N that was more than 40 mg NO_3-N L^{-1} compared with less than 3 mg NO_3-N L^{-1} of the other replications, following rodent activity over one of their lysimeters. Besides the inherited variability of each soil, turfgrass models have to be able to incorporate cultural practices unique in turfgrass systems which might increase the spatial variability of solute flow. Cultivation (aerification) is a frequent practice in turfgrass management used to overcome the detrimental effects of soil compaction, reduce thatch accumulation and as topdressing precursor (Carrow and Petrovic 1992). Cultivation in this sense refers to the practice by which openings are made on the surface of established turf (Turgeon 2004). Given the right conditions these man-made macropores have the potential to conduct water and solutes much faster than the soil matrix. More specifically, when the total inputs (precipitation plus irrigation) exceed the infiltration capacity of the soil matrix, water and solutes are channelled into the macropores creating a short-circuiting flow (Beven and Germann 1982; Edwards et al. 1992; Morales et al. 2010). Edwards et al. (1989) found that in a 5 month period a mass equivalent to 711 g ha^{-1} NO_3 was lost through earthworm holes of *Lumbricus terrestris* L. The burrowing activity of this particular species resembles cultivation since both are perpendicular to the soil surface and often have a diameter of 5 mm or greater.

The objective of this study is to investigate whether man made macropores created during turfgrass cultivation have similar detrimental effects on nitrate groundwater pollution as the biological macropores. Three turfgrass cultivation treatments and two soil types were examined for their leaching potential of two nitrogen sources under different irrigation regimes.

Materials and Methods

Experimental set up

The experimental design was a factorial completely randomized block design. The first factor was the type of the profile (either USGA sand profile or sandy clay profile). The second factor was the type of cultivation having three different cultivation treatments (shallow hollow tine cultivation, deep drill cultivation, and high pressure water injection) and an uncultivated control. All treatments were randomly assigned within each of the three blocks.

Lysimeter construction

The study was performed at Kenneth Post greenhouse facilities at Cornell University, Ithaca, NY, USA. Twenty four lysimeters were constructed from a PVC pipe with a height of 460 mm and internal diameter 300 mm. The bottom of each lysimeter was made from black PVC sheet having a 12.5 mm draining hole in the middle with a valve and a tubing to collect leachate. The bottom was attached and sealed to the upper part of the lysimeter.

Twelve of the lysimeters were filled with a sandy clay soil that was screened through a 100 × 50 mm screen. A thin layer of gravel (3–7 mm) was placed just above the drain outlet. The other twelve lysimeters were filled with 100 mm of gravel at the bottom, 50 mm of coarse sand in the middle and 305 mm of fine sand at the top, simulating a US Golf Association style putting green (Usga 1993). All the constituents for both profiles were analyzed for particle size distribution (Table 1) and for physical and chemical properties (Table 2).

Compaction of the profiles

After the lysimeters were filled with the appropriate soil profile, they were compacted with a hydraulic press to produce a uniform packing. The lysimeters containing the sandy profile were pressed at 1.380 10^{-3} MPa while the lysimeters containing the sandy clay profile were pressed at 0.552 10^{-3} MPa. The lysimeters were sodded with washed sod of creeping bentgrass (*Agrostis stolonifera ssp. palustris* Huds. var. 'Providence') that grew for two months in the greenhouse.

After the two month period additional compaction was applied to all lysimeters with a free falling weight technique in order to simulate the compaction that exists in golf courses. A metal weight (5.3 kg) was left to fall on a circular metal plate that fitted tightly on the top of the lysimeters. The weight was guided by a metal rod in order to create uniform and replicable compaction. The weight was left to fall from a height of 55 cm thirty times on the sandy profiles and ten times from the same height for the sandy clay profiles.

Shallow hollow tine cultivation (95 mm deep) was done using a hollow tine (19 mm I.D.) that fitted at the end of a heavy steel bar. The metal bar with the tine at one end was dropped through a copper tube that was adjoined onto a circular metal plate placed on top of the lysimeters. Each drop created a single hole then the core was removed from the tine, the plate was rotated 90° and another drop was performed until each lysimeter had four holes having a spacing of 110 × 110 mm. The second treatment was the deep drill cultivation. Four holes were

Table 1. Particle size distribution of the substrate and drainage materials used in the greenhouse and field lysimeter studies.

Particle size distribution	Sandy clay	Root zone sand	Coarse sand	Particle size distribution	Gravel
		(%)		(mm)	(%)
Sand (mm)	46.80	96.70	95.60		
> 2.00	6.55	5.90	13.04	12.5	6.0
2.00–1.00	12.28	12.85	17.75	9.5	30.0
1.00–0.50	24.09	27.61	23.33	6.3	50.0
0.50–0.25	27.04	41.83	27.08	4.0	12.0
0.25–0.10	18.49	10.55	15.88	2.0	1.0
0.10–0.05	10.57	1.20	2.91	1.0	0.0
< 0.05	0.98	0.06	0.01	< 1.0	1.0
Silt	8.90	0.80	1.20		
Clay	44.30	2.50	3.20		

Table 2. Physical and chemical properties of the sand and the sandy clay soil used in the greenhouse and field study. Values are means of 3 replications ± standard error.

Soil	Cultivation type	Bulk density ($g\ cm^{-1}$)	Water retention at 400 mm ($cm^3\ cm^{-3}$)	Saturated hydraulic conductivity ($mm\ h^{-1}$)	Organic matter (%)	pH	NO_3 available ($mg\ kg^{-1}$)
Sand	Shallow	1.56 (± 0.02)	8.46 (± 0.23)	202.70 (± 24.84)	0.44 (± 0.04)	8.37 (± 0.15)	
	Deep drill	1.54 (± 0.03)	8.89 (± 0.11)	223.51 (± 41.89)	0.49 (± 0.06)	8.45 (± 0.25)	3.60
	Water injection	1.57 (± 0.03)	8.76 (± 0.39)	206.74 (± 10.18)	0.48 (± 0.08)	8.56 (± 0.09)	
	Uncultivated	1.57 (± 0.02)	8.74 (± 0.48)	212.39 (± 11.90)	0.47 (± 0.06)	8.38 (± 0.15)	
Sandy Clay	Shallow	1.46 (± 0.04)	33.42 (± 1.26)	9.01 (± 9.31)	2.68 (± 0.19)	7.12 (± 0.23)	
	Deep drill	1.50 (± 0.03)	35.29 (± 1.93)	6.32 (± 10.84)	2.69 (± 0.19)	6.72 (± 0.20)	22.81
	Water injection	1.53 (± 0.03)	35.46 (± 0.84)	21.06 (± 30.29)	2.61 (± 0.20)	6.72 (± 0.07)	
	Uncultivated	1.45 (± 0.07)	33.42 (± 2.15)	10.22 (± 11.44)	2.48 (± 0.08)	6.98 (± 0.08)	

made in each lysimeter using a hand drill (375 rpm) and a bit (254 mm length and 19 mm wide) taken from a commercial unit (Floid-MacCay Deep Drill) at 110 × 110 mm spacing. For the water injection treatment, a commercial unit was used (Hydroject 3000, Toro Co., Minneapolis, MN). A pit 450 mm deep was dug in which a single lysimeter was placed. The lysimeters were then covered with a plywood that had a 190 × 300 mm opening. Then the water injection cultivator was run over the plywood opening, performing four injections per lysimeter at 76 × 140 mm spacing.

Turfgrass maintenance

Lysimeters were mowed three times every week at 6 mm height using a grass shear (Disston HB-4). During the study the clippings were removed and collected with a vacuum cleaner. The clippings were oven dried at 65 °C for 48 h and their dry weight was determined. At the end of the study all clippings from each lysimeter were mixed together, ground, and an averaged value of N contained in the leaf tissue was obtained using a Micro Kjeldahl nitrogen analysis (Rym and Milham 1976).

The lysimeters were irrigated using a peristaltic pump that delivered water under pressure through a full cone pesticide nozzle (Sprayco 111820, Spraying System Co.). The nozzle was held 300 mm above the surface of the lysimeter creating a uniform coverage of the canopy. Tap water was used for irrigation and a sample was stored and analyzed for NO_3 concentration.

Studies setup

Three studies were performed in the greenhouse using the same lysimeters. In the first study the lysimeters were fertilized with a solution containing 5 mmoles KNO_3, 1 mmoles $NH_4H_2PO_4$, 2 mmoles NH_4NO_3, 0.5 mmoles $mgSO_4$ and 0.1 mmoles $CaCl_2$. The sandy profiles were also supplemented with half strength of Hoaglands' micronutrient solution. The fertilizer solution was applied at a rate of 24 kg N ha^{-1}. From then on the same solution was applied in weekly intervals at a rate of 12.2 kg N ha^{-1}.

Daily irrigation was added in order to exceed the predetermined water holding capacity of each lysimeter by 6.8 mm (500 mL) to encourage leaching. Before the initiation of the study, waterholding capacity was determined by saturating the lysimeters slowly from the bottom and then draining them for 24 h using a strain gage (Omega, Model LCC, Omega Engineering Inc.).

In the second study turfgrass was fertilized using the same fertilizer source at a rate of 24.4 kg N ha^{-1}. In order to investigate macropore flow under higher flow rates, the total daily irrigation ranged from 13.7 to 27.4 mm and was applied every 6 to 8 h, to simulate an overwatering regime during a rainy period.

In the third study $(NH_4)_2SO_4$ was utilized as N source at a rate of 49 kg N $ha^{-1}$and $CaCl_2$ was applied as a tracer at a rate of 147 kg Cl ha^{-1}. In this case the daily irrigation rate was 13.7 mm and the study simulated NO_3 leaching from turfgrass sites subjected to increased N inputs.

Leachate collection and nitrate analysis

The leachate from the free draining lysimeters was collected in 1 L Nalgene bottles that were placed in a water bath. A peristaltic pump was used to circulate water from a cooler to the water bath keeping the temperature at 4–6 °C in order to prevent denitrification of NO_3. The samples were weighed to determine the effluent volume and then refrigerated at 3–4 °C until they were analyzed for nitrate concentrations.

Nitrate analysis for all studies was performed using a modified salicylic acid colorimetric technique (Vendrell and Zupancic 1990). Data were subjected to statistical analysis using JMP Version 8 statistical software (SAS Institute Inc., Cary, NC) following multivariate analysis of variance (MANOVA). Means were separated using Fisher's protected least significant difference at a 0.05 P level ($P < 0.05$).

Results and Discussion

With the daily irrigation of 6.8 mm in excess of the predetermined lysimeter water holding capacity, nitrates were detected in the effluent of the cultivated sand profiles at 1 L of effluent volume (Fig. 1). The breakthrough curve (BTC) of the NO_3^- is depicted in Fig. 1. The NO_3 of the cultivated profiles broke through earlier than for the uncultivated profiles indicating partial bypassing due to macropore flow. The cultivated profiles exceeded the Health Advisory Limit (HAL) for drinking water of 10 mg NO_3-N L^{-1} and peaked at 14 mg NO_3-N L^{-1}, while the uncultivated profiles reached 12 mg NO_3-N L^{-1}. The peak of NO_3 BTCs were similar to the ones reported by Snyder et al. (1984) using NH_4NO_3 at a rate of 49 kg N ha^{-1} and 8 mm d^{-1} of irrigation on sandy soil in Florida.

With the greater irrigation rate (13.7 to 27.4 mm) in the second study, nitrates were detected from the sand profiles at 0.7 L of effluent volume, and at 3 L of effluent volume all sand profiles exceeded the HAL (Fig. 2). The slope of the BTC of the uncultivated profiles was not as

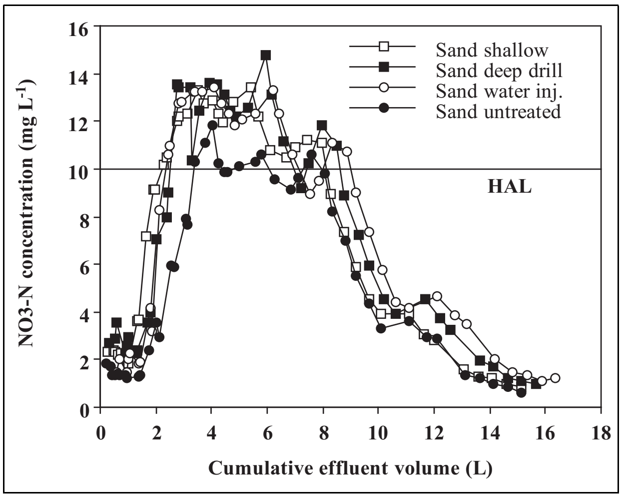

Fig. 1. Cultivation effects on breakthrough curve for NO_3-N in the sand profiles using the solution fertilizer and daily irrigation of 6.8 mm in excess of the water holding capacity of the lysimeters. The dotted line represents the Health Advisory Level (HAL) for NO_3-N in drinking water. Values are means of three replications.

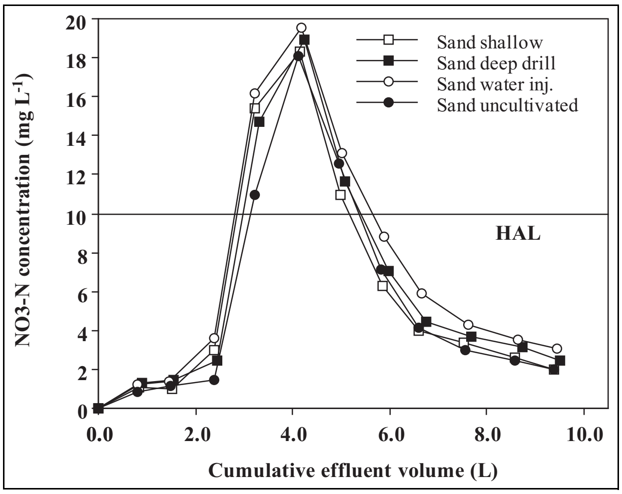

Fig. 2. Cultivation effects on NO_3-N breakthrough curve for the sand profiles using solution fertilizer and a daily irrigation of 13.7 to 27.4 mm (overwatering). The dotted line represents the Health Advisory Level (HAL) for NO_3-N in drinking water. Values are means of three replications.

steep compared with the BTC from the cultivated profiles. However, the differences in BTCs' shape were not significant and were less pronounced compared with the low irrigation regime. These results are opposite the findings of Beven and Germann (1982); Germann et al. (1984) that indicated that macropore flow is more pronounced as the intensity and the amount of the inputs (precipitation and irrigation) increases. Consequently, more pronounced differences between cultivated and uncultivated profiles would be expected with overwatering (higher irrigation rate) compared with the low irrigation. These results suggested that an additional factor or a different mechanism was responsible for the differences observed with the low irrigation regime. It was noticed that with the low irrigation rate the canopy was behaving as a hydrophobic surface, probably due to the warm greenhouse environment in conjunction with the interval between subsequent irrigation events (24 h). The temporary hydrophobic response of the turfgrass canopy inhibited infiltration through the soil matrix and channelled the applied water and chemicals into the macropores producing the observed differences. For the overwatering irrigation regime the applications were split into three and thus irrigation was applied every 6 to 8 h. Therefore, the surface was kept adequately moist preventing the hydrophobic phenomena. The hydrophobic phenomena of the turf sward and its effect on water flow at low and high water inputs were verified with the use of blue dye followed by excavation of the lysimeters (Nektarios et al 2004, 2007).

Nitrate leaching from the sandy clay profiles was minimal for both the high and low irrigation rates (data not presented). Concentrations ranged from 0 to 1 mg NO_3-N L^{-1}, thus preventing the detection of any differences between cultivation treatments. Brown et al. (1982) recovered more than 10 mg NO_3-N L^{-1} for 25 d from a sandy loam soil with 12 mm d^{-1} of irrigation and NH_4NO_3 as the fertilizer source. However, their N application rate was much higher (163 kg N ha^{-1}) than the rates used in our studies. There are three factors that could be responsible for the minimal leaching observed in the sandy clay soil profiles, namely losses by denitrification, dilution, and/or plant uptake. Denitrification, if it occurred at all is expected to be higher in a sandy clay soil rather than a sand soil due to the increased soil moisture content and the elevated organic C content (Table 2). Burford and Bremner (1975) found a good correlation between the organic C and denitrification rates, while Chaterpaul et al. (1980) found that denitrification rates increased as the soil texture was becoming finer. Dilution is also expected to be more efficient in a sandy clay soil because of the increased water holding capacity compared to the sand (Table 2). In addition, it was observed that the cultivation holes in the sandy clay profiles were filled with stagnant water after each irrigation. Water infiltrated slowly in approximately 20–30 min. after the application which indicated that water and chemical transport was slow due to the discontinuous morphology of the cultivation holes (Nektarios et al. 2007).

In these two greenhouse studies (first and second), the total dry weight of the clippings from the sandy clay soil profiles was significantly different compared with the sand profiles (Table 3). Furthermore, the sandy clay profiles exhibited a better turf quality for the duration of the study and had a significant higher N recovery in clippings (Table 3). This indicated that N accumulation in the clippings was significantly greater in the sandy clay profiles compared with the sand ones, explaining in part the differences in NO_3 leaching between the two soil types. The N take-up by the plants was related to the increased differences observed in NO_3-N total mass loss between sand and sandy clay soil (Table 4).

Using $(NH_4)_2SO_4$ as N source and 13.7 cm of daily irrigation (third study), the recovered NO_3-N in the leachate from the sand profiles was about three to four times greater compared with the previous two studies (Fig. 3). With the deep drill cultivation the highest concentration of nitrates (55 mg NO_3-N L^{-1}) in the effluent was detected at 4.2 L of cumulative effluent volume. With the shallow hollow tine cultivation effluent NO_3 concentration peaked at 54 mg NO_3-N L^{-1} at 4.0 L, while the water injection and the uncultivated control peaked at 45 mg NO_3-N L^{-1} at 6.1 and 6.7 L of cumulative effluent volume. The excessive NO_3 leaching was probably caused by limited N plant uptake as a result of plant sufficiency in N.

The shape of the BTCs from the sand profiles was similar for the deep and shallow core cultivation treatments, indicating comparable pathway and velocities of NO_3 transport. The slower rise of the BTC for Cl of the uncultivated lysimeters indicated a slower pathway of the solutes (via soil matrix) compared with the partial bypassing via macropore flow in the cultivated profiles (Fig. 4).

In the sandy clay profiles nitrate leaching was less from the shallow and deep drill cultivated profiles due to a temporary storage of water in the cultivation holes and gave water the time to infiltrate sideways into the cultivation hole. Consequently the water flowed more uniformly through the column than for the sandy profiles. This resulted in a lower velocity of the water and the dissolved nitrates. Deep drill cultivated profiles had the fastest velocity and the shortest time for nitrate to be taken up by the pants or to denitrify and therefore reached a NO_3-N concentration of 20 mg L^{-1} (Fig. 3). The deep drill BTC had a smaller slope and lower peak compared with the sandy profiles due to the increased variability in the velocity of the solute transport and the higher water content (Fig. 3). Nitrate concentration peaked 9 DAA in the deep drill cultivated sandy clay soil profiles compared with 7 DAA for the deep cultivated sand profiles and had approximately 3 times smaller NO_3-N concentration from the sand profiles.

Even though core cultivation has been shown to have some influence on solute flow past the root zone (Nektarios et al. 2007), according to nutrient and tracer studies involving macropores (Edwards et al. 1992) more pronounced differences were expected. To date, the effects of macro-

Table 3. Soil, irrigation and cultivation effects on total dry weight and N content of the clippings during the first study using the fertilizer solution. Values are means of three replications†.

Soil	Cultivation type	Low irrigation†		High irrigation†	
		Pooled NH3-N (%)	Total dry weight (g)	Pooled NH3-N (%)	Total dry weight (g)
Sand	Shallow	2.09 (± 0.11)	5.02 (± 0.23)	1.54 (± 0.14)	2.06 (± 0.13)
	Deep drill	1.85 (± 0.03)	5.76 (± 1.41)	1.11 (± 0.08)	2.00 (± 0.34)
	Water injection	2.11 (± 0.20)	3.87 (± 0.78)	0.95 (± 0.21)	2.03 (± 0.12)
	Uncultivated	1.90 (± 0.25)	4.72 (± 0.62)	1.07 (± 0.09)	1.99 (± 0.04)
Sandy Clay	Shallow	3.65 (± 0.04)	8.50 (± 0.73)	3.24 (± 0.10)	3.84 (± 0.16)
	Deep drill	3.57 (± 0.15)	9.48 (± 1.25)	3.25 (± 0.05)	3.91 (± 0.25)
	Water injection	3.65 (± 0.06)	8.56 (± 0.32)	3.75 (± 0.17)	4.04 (± 0.36)
	Uncultivated	3.60 (± 0.04)	9.42 (± 0.19)	3.54 (± 0.08)	3.93 (± 0.15)
ANOVA Table					
Source	df				
Soil (S)	1	***	***	***	***
Cultivation (C)	3	NS	NS	NS	NS
S × C	3	NS	NS	NS	**

† Low irrigation was 6.8 mm d^{-1} in excess of container capacity and high irrigation was 13.7 to 27.4 mm d^{-1}.
, * Significant at 0.01 and 0.001 probability level, respectively; NS not significant at P > 0.05.

Table 4. NO_3-N mass loss from each treatment for the three studies. Values are means of three replicates (± standard error†).

Fertilizer type / Soil	Cultivation type	Solution fertilizer Low irrigation†	Solution fertilizer High irrigation†	$(NH_4)_2SO_4$ High irrigation†
Sand	Shallow	102.7 (± 17.6)	68.0 (± 2.74)	271.0 (± 20.0)
	Deep drill	110.1 (± 8.0)	71.3 (± 2.86)	244.8 (± 7.7)
	Water injection	112.0 (± 9.9)	80.5 (± 0.16)	281.5 (± 64.7)
	Uncultivated	82.6 (± 15.9)	63.7 (± 8.95)	229.5 (± 43.7)
Sandy Clay	Shallow	5.7 (± 0.5)	5.0 (± 0.45)	–
	Deep drill	6.1 (± 0.5)	6.4 (± 1.59)	154.2 (± 29.9)
	Water injection	6.0 (± 0.5)	5.0 (± 0.45)	–
	Uncultivated	6.2 (± 0.2)	4.4 (± 0.26)	–

† Low irrigation was 6.8 mm d^{-1} in excess of container capacity, high irrigation was 13.7 to 27.4 mm d^{-1}. Irrigation at the $(NH4)_2SO_4$ study was 13.7 mm d^{-1}.
– Data not included in the analysis.

porosity on solute flow have been studied in laboratory, field and/or monolith experiments where the macropores were continuous from the surface to the bottom of the system (Czapar et al. 1992) with the exception of Allaire-Leung et al. (2000) who investigated the situation of a discontinuous macropore. In this study, the lack of connectivity and continuity of the artificial macropore system prohibited the occurrence of major differences between

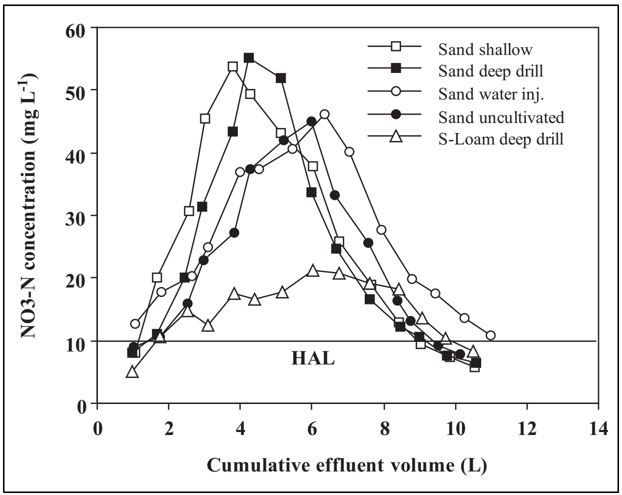

Fig. 3. Cultivation effects on NO_3-N breakthrough curve for the sand profiles using $(NH_4)_2SO_4$ and daily irrigation of 13.7 mm (third study). Values are means of three replications. The dotted line represents the Health Advisory Level (HAL) for NO_3-N in drinking water.

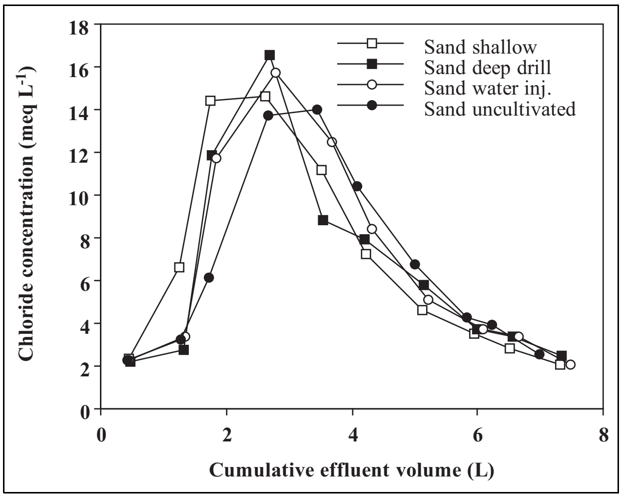

Fig. 4. Cultivation effects on chloride breakthrough curve from sand profiles using a daily irrigation of 13.7 mm. Values are means of three replications.

cultivated and uncultivated profiles. In addition, Murphy et al. (1993) found that core cultivation of noncompacted soils caused a 30 % reduction of the hydraulic conductivity or had no effect on the hydraulic conductivity of compacted soils. The same authors (Murphy et al. 1993) found that following core cultivation water infiltration decreased under field conditions, probably because tine penetration caused compaction on the sides and the bottom of the core holes as it was reported by Petrovic (1979).

Conclusions

The current study is important for turfgrass management since it provides information that turfgrass cultivation may have a negligible effect on nitrate leaching to groundwater. Irrigation rate was found to be a significant factor in the mobility of the chemicals through the vadose zone. However, with the rates that were used in these studies artificial macropores do not seem to pose an additional threat to groundwater. The sand profiles were prone to excessive leaching with or without macropores and the leaching potential depended on plant nutritional levels and irrigation-precipitation rates.

The factors that should be taken into account in modeling the fate of nitrogenous fertilizers from turfgrass systems are: irrigation-precipitation rate and intensity, soil hydrophobicity, plant nutritional level at the time of the fertilizer application, soil type, natural macroporocity and distance from the end of the macroporous system to the underlying aquifers.

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