

Nitrogen Leaching in Sand-based Rootzones Amended with Inorganic Soil Amendments and Sphagnum Peat

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ABSTRACT. sand-based rootzones are specified for golf course putting greens because they resist compaction and maintain drainage, even under heavy traffic. Although sands provide favorable physical properties, nutrient retention is generally poor and soluble nutrients like nitrogen (N) are prone to leaching. Laboratory experiments were conducted to evaluate several inorganic soil amendments (clinoptilolite zeolite (CZ), diatomaceous earth, and two porous ceramics), which varied in cation exchange capacity (CEC), and sphagnum peat for their ability to limit N leaching. Columns (35 cm tall \times 7.6 cm diameter) were filled with 30 cm of sand-amendment mixtures (8:2 v/v) and NH_4NO_3 was applied in solution at a N rate of $50 \text{ kg}\cdot\text{ha}^{-1}$. Leaching was initiated immediately using 2.5 pore volumes of distilled water in a continuous pulse. Leachate was collected in 0.1 pore volume aliquots and analyzed for $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$. All amendments significantly decreased NH_4^+ leaching from 27% to 88% which was directly proportional to the CEC of the amendments. By contrast, NO_3^- losses were consistently high, and no amendment effectively decreased loss compared to nonamended sand. Two amendments with the highest CECs, CZ and a porous ceramic, were selected to further study the effects of amendment incorporation rate, depth, and incubation time on N leaching. Ammonium but not NO_3^- leaching was decreased with increasing amendment rate of both products. At 10% amendment (v/v) addition, only 17% to 33% of applied NH_4^+ leached from the amended sands. Depth of amendment incorporation significantly affected NH_4^+ leaching, with uniform distribution through the entire 30 cm tall column being more effective than placement within the upper 2.5 or 15 cm. Allowing the NH_4NO_3 to incubate for 12 or 24 hours following application generally did not affect the amount leached. These results suggest $\text{NH}_4^+\text{-N}$ leaching is inversely related to CEC of the root-zone mixture and that uniform distribution of these CEC enhancing amendments in the root-zone mixtures reduced N leaching to a greater extent than nonuniform distribution.

Sand-based golf course putting green rootzones are often constructed with sand contents of 90% or more to minimize compaction and maintain high infiltration. While sand provides favorable physical properties for turfgrass growth, it is a poor medium for nitrogen (N) retention. Putting greens often receive as much N as $300 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ from highly soluble sources like ammonium nitrate or urea. During turfgrass establishment N applications of $490 \text{ kg}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ are not uncommon (Beard, 1982). Soluble N applications, porous media, and regular irrigation create the potential for large N leaching losses (Brown et al., 1982).

It has been well documented that a dense mature turfgrass system is very effective in capturing N. Mancino and Troll (1990) monitored leaching losses of nitrate ($\text{NO}_3^-\text{-N}$) and ammonium ($\text{NH}_4^+\text{-N}$) nitrogen for several readily soluble and slowly soluble N fertilizers on 10 month old creeping bentgrass [*Agrostis stolonifera* L. var. *palustris* (Huds.) Farw.] grown in a sand medium amended with 20% sphagnum peat (v/v). They reported that $<0.5\%$ of applied N leached, even when irrigated at moderately heavy rates ($38 \text{ mm}\cdot\text{wk}^{-1}$). Nitrate-N was the major form leached while $\text{NH}_4^+\text{-N}$ losses were negligible. Miltner et al.,

(1996) found that an established turf was very effective for retaining N in the rootzone. They grew Kentucky bluegrass (*Poa pratensis* L.) on a fine sandy loam and reported that only 0.23% of applied labeled fertilizer N leached over a 2-year period.

While there may be low potential for $\text{NO}_3^-\text{-N}$ leaching from mature turfgrass systems, the same is not true for immature turfgrass. Frequent light irrigation is required to ensure seedling survival in well-drained sands. Further, the shallow root system of an immature turf is less efficient at N absorption, which would increase the leaching potential. Brauen and Stahnke (1995) reported that N leaching was greater during year one than in year two of a newly established creeping bentgrass putting green. They suggested this was due to more extensive rooting, increased thatch, and increased rootzone organic matter in year two. Bowman et al. (1998) reported similar affects of root development on nitrate leaching and found that $\text{NO}_3^-\text{-N}$ losses were greater in shallow versus deeply rooted creeping bentgrass clones.

Most sand-based golf greens are amended with stabilized organic matter, such as sphagnum peat, to improve nutrient and water retention. Recently, many inorganic soil amendments [porous ceramics, diatomaceous earth products, and clinoptilolite zeolites (CZs)] have been introduced as alternatives for peat moss. These products are not susceptible to biological degradation and might have a longer effect than organic amendments. Several researchers have reported that CZ incorporation dramatically decreased N leaching from sand media (Huang and Petrovic, 1994; Nus and Brauen, 1991). Ferguson and Pepper (1987) attributed the lower leaching losses to the high NH_4^+ ion retention of CZ. MacKown and Tucker (1985) also reported lower NH_4^+ losses with zeolites and found that as incorporation rate increased, N loss decreased significantly. This is not surprising since some CZs have a theoretical cation exchange capacity

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Table 1. Particle size distribution of sand and inorganic amendments.

Rootzone component	Particle size (mm)						
	> 2.0	1.0	0.50	0.25	0.10	0.05	< 0.05
				(g·kg ⁻¹)			
Sand	2	51	364	473	104	5	0
Clinoptilolite zeolite	0	1	242	615	139	1	3
Diatomaceous earth	0	5	446	534	10	5	<1
Porous ceramic 1	0	2	714	272	14	<1	<1
Porous ceramic 2	0	3	871	108	11	7	<1

(CEC) of 220 cmol_c·kg⁻¹ (Ming and Mumpton, 1989); increasing the CZ incorporation rate would thus increase CEC. While much information exists for CZ, comparable data for other commercial inorganic amendments are lacking. Therefore, the objective of this study was to determine if enhancing the CEC of sand-based rootzones with soil amendments of varying CECs would limit N leaching and to determine if CEC was the main mechanism for controlling NH₄⁺ leaching. Consistent with this hypothesis it was speculated that if CEC is the primary mechanism affecting N leaching then NO₃⁻ leaching would remain largely uninfluenced. The effects of incorporation rate of CEC enhancing amendments, incorporation depth and N incubation time (time between N application and leaching) were also examined.

Materials and Methods

Four laboratory experiments were conducted to investigate the relationship between CEC and N leaching in sand-based rootzones using soil amendments of varying CEC. Experimental root-zone media were prepared by amending a locally available washed quartz sand (Black Creek Mining Co., Conway, S.C., particle distribution, Table 1) with the following products: sphagnum peat (973 g·kg⁻¹ organic matter loss on ignition at 500 °C, Bordnamona Co., Dublin, Ireland); clinoptilolite zeolite (ECOLITE, Western Organics, Inc., Tempe, Ariz.); diatomaceous earth containing 5% of a clay binder (ISOLITE, Sundire Enterprises, Arvada, Colo.); and two porous ceramic products, (PROFILE, Applied Industrial Materials Corp., Buffalo Grove, Ill.) and (GREENSCHOICE, Premier Environmental Products, Inc., Houston, Texas), hereafter referred to as porous ceramic one (PC1) and porous ceramic two (PC2), respectively.

Selected physical properties and chemical properties of the amendments and root-zone media were determined (Tables 1 and 2). Particle size distribution of the quartz sand and the

inorganic amendments were determined by mechanical sieving. Saturated hydraulic conductivity of selected root-zone mixtures was determined by the constant head method (Klute and Dirksen, 1986) with results adjusted to 20 °C (Table 2). Pore size distributions of selected root-zone mixtures were determined, total porosity was calculated using measured bulk density and particle density determined by the pycnometer method (Blake and Hartge, 1986). Macroporosity, or air-filled porosity, was calculated by subtracting the -0.003 MPa water content, determined by the water desorption method (Danielson and Sutherland, 1986), from total porosity. Capillary porosity was calculated as the difference between total porosity minus air-filled porosity (USGA, 1993). Cation exchange capacity (CEC) of selected rootzone mixtures was determined by 1 mol·L⁻¹ ammonium acetate extraction, at pH = 7 (Table 2). The CECs of the inorganic amendments ECOLITE, GREENSCHOICE, ISOLITE, PROFILE, and sphagnum peat were 185 to 220, 1.0, 0.8, 33.6, and 75 to 100 cmol_c·kg⁻¹, respectively (values from manufacturer's product literature).

Four experiments were conducted to quantify the rootzone amendments for their capacity to limit N leaching following application of ammonium nitrate (NH₄NO₃). 1) Amendments were compared when mixed with quartz sand at 20% amendment, by volume. Peat additions were equivalent to 1.2% organic matter by weight. Based on data from the first experiment, CZ and PC1 were selected for further study. 2) The effect of amendment rate on N leaching was determined using sand mixtures containing 1%, 5%, 10%, and 20% (v/v) incorporated throughout the entire 30 cm rooting media. 3) The effect of depth of amendment was investigated by incorporating 10% (v/v) of each material into the top 2.5 cm, 15 cm or 30 cm of the rooting media. Nonamended sand was used as a control. 4) The effect of incubation time on N leaching was determined. The ammonium nitrate solution was applied to pure sand and sand amended with either CZ or PC1

Table 2. Selected physical and chemical properties of selected sand amendment root-zone mixtures used in nutrient retention experiments.

Amendment	Rate (% by vol.)	Hydraulic conductivity (cm·h ⁻¹)	Bulk density (g·cm ⁻³)	Total porosity (cm ³ ·cm ⁻³)	Capillary porosity ^z (cm ³ ·cm ⁻³)	CEC (cmol _c ·kg ⁻¹)	pH
Nonamended	---	316 a ^y	1.62	0.413	0.174	0.8	5.3
Clinoptilolite zeolite	10	212 bc	1.60	0.437	0.196	5.3	5.4
	20	217 bc	1.56	0.399	0.165	9.6	5.6
Diatomaceous earth	20	288 ab	1.53	0.447	0.204	0.9	5.3
	10	232 bc	1.57	0.431	0.180	2.4	6.3
Porous ceramic 1	20	197 c	1.52	0.435	0.194	4.6	6.8
	20	326 a	1.56	0.423	0.182	1.1	6.3
Porous ceramic 2	20	100 d	1.44	0.489	0.197	4.2	5.1

^zCapillary porosity determined at -0.003 MPa tension.

^yMean separation by Fisher's protected LSD, *P* = 0.05.

Table 3. Peak concentration and percentage loss of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the effluent of sand amended at 20% by volume with four inorganic soil amendments and sphagnum peat.

Soil amendment	$\text{NH}_4\text{-N}$		$\text{NO}_3\text{-N}$	
	Peak concn ($\text{mg}\cdot\text{L}^{-1}$)	Total loss (%)	Peak concn ($\text{mg}\cdot\text{L}^{-1}$)	Total Loss (%)
Nonamended	59.3 a ^z	96.2 a	78.9 a	98.1 a
Clinoptilolite zeolite	3.3 c	7.8 e	52.9 bc	99.2 a
Diatomaceous earth	23.9 b	63.9 b	39.4 c	97.8 ab
Porous ceramic 1	8.4 c	21.3 d	52.3 bc	96.1 ab
Porous ceramic 2	26.9 b	69.4 b	55.7 b	95.4 b
Sphagnum peat	11.0 c	37.7 c	51.0 bc	95.1 b

^zMean separation within columns by Fisher's protected LSD, $P = 0.05$.

(20% v/v). The tops of the columns were covered with small plastic disks to prevent evaporation and incubated for 0, 12, or 24 h before leaching.

Experimental rootzones were constructed as two-piece columns. The base of the column was constructed from a polyvinyl chloride cylinder (7.6 cm i.d. \times 10 cm tall with a wall thickness of 0.48 cm) with a metal screen attached at the bottom. This was filled with 10 cm of gravel meeting USGA specifications for golf putting greens (USGA, 1993). An acrylic cylinder (7.6 cm i.d. \times 35 cm tall with a wall thickness of 0.42 cm) to hold the root-zone media was attached to the top of the gravel base with electrical tape. Each premixed, preweighed, air-dried rooting medium was slowly poured into the acrylic column in one continuous step, which minimized layering. After installation the medium was compacted to predetermined bulk density values (Table 2) by lightly tapping the column on a hard surface until the mixture was 30 cm deep. Packed rootzones were then placed in a plastic container of equivalent height and incrementally saturated with tap water from the bottom up until ponding at the root-zone surface was observed. After 24 h at saturation, each column was placed on a screen and allowed to drain for 24 h. During drainage, the top of each column was loosely covered with a small plastic disk to prevent evaporation.

After drainage, 5 mL of a solution containing 22.5 mg $\text{NH}_4\text{NO}_3\text{-N}$ (AN-N) (equivalent to N at 50 $\text{kg}\cdot\text{ha}^{-1}$) was applied to the surface of each column. In Expts. 1 to 3, 2.5 pore volumes, (≈ 1.8 L, based on the calculated total porosity of the rootzone mixtures), of twice-distilled water was applied immediately following nutrient application, as a continuous pulse to the root-zone surface. A small styrofoam block was placed on the root-zone surface to absorb the initial impact of the water as it was poured. This minimized surface disturbance and facilitated even water infiltration. In Expt. 4, the columns were leached at 0, 12, and 24 h after nutrient application. Leachate was collected in 0.1 pore volume aliquots and analyzed for $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ by the rapid diffusion method (Carlson, 1986).

Statistical analysis. The first experiment was conducted as a completely randomized design with three replicates of each mixture. Each of the three subsequent studies employed a factorial arrangement of treatments with a nonamended sand treatment included as a control. The factorial treatments were as follows: Expt. 2 (2 amendments \times 4 rates); Expt. 3 (2 amendments \times 3 depths); and Expt. 4 (3 amendments \times 3 incubation times). Data were analyzed using the SAS general linear model procedure (SAS Inst., Inc., 1996). Means were separated using Fisher's protected LSD and preplanned orthogonal contrasts where appro-

priate (Steel et al., 1997). In Expts. 2 to 4, results from amended sands were compared against the nonamended sand control using Dunnett's test (Steel et al., 1997). Regression analysis was performed on the rootzone mixture physical and chemical properties versus $\text{NH}_4\text{-N}$ leaching to determine the major factor determining N leaching (Steel et al., 1997).

Results

EXPERIMENT 1. A wide range in $\text{NH}_4\text{-N}$ leaching was observed from the various rootzone amendment mixtures (Table 3). Ammonium nitrogen appeared rapidly in the effluent from all rootzone media with peak concentrations occurring at ≈ 0.5 pore volumes (Fig. 1). This pattern was consistent in all four experiments (data not presented). Significantly higher peak $\text{NH}_4\text{-N}$ concentrations and more cumulative $\text{NH}_4\text{-N}$ leached from nonamended sand than from the 20% (v/v) amended mixtures (Table 3).

In contrast, $>90\%$ of applied $\text{NO}_3\text{-N}$ was recovered in the leachate of all rootzone mixtures in all experiments (Tables 3–5). In general, nonamended sand and most amended sand mixtures in all experiments were similar regarding $\text{NO}_3\text{-N}$ leaching with only a few exceptions. Peak $\text{NO}_3\text{-N}$ concentrations were greatest for nonamended sand (78 $\text{mg}\cdot\text{L}^{-1}$) and slightly less (50 $\text{mg}\cdot\text{L}^{-1}$) for amended media. The only amendments that significantly decreased cumulative $\text{NO}_3\text{-N}$ compared to the nonamended sand control, were sphagnum peat and PC2 at the 20% rate. However, even at these high amendment incorporation rates more than 95% of applied $\text{NO}_3\text{-N}$ leached from the rootzone mixtures (Table 4).

EXPERIMENT 2. As incorporation rates for the two most effective amendments, PC1 and CZ, increased from 1% to 20%, loss of $\text{NH}_4\text{-N}$ and the peak effluent concentrations decreased in a stepwise manner, with the 20% rate resulting in the least $\text{NH}_4\text{-N}$ loss for both amendments (Table 4). No differences in N retention between the two materials were observed, except at the 20% rate, where significantly less $\text{NH}_4\text{-N}$ leached from the CZ amended sand which had a higher CEC.

EXPERIMENT 3. Incorporation depth of CZ and PC1 at 10% by volume, significantly affected $\text{NH}_4\text{-N}$ leaching. Increasing amend-

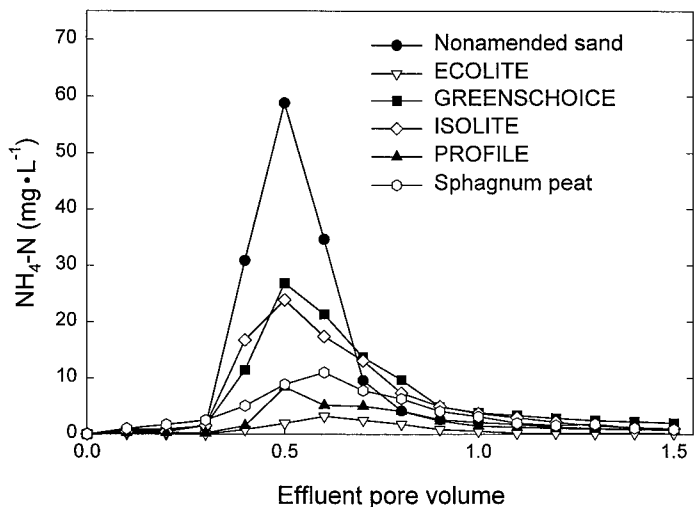


Fig. 1. Ammonium concentrations in the leachate of nonamended sand and sand amended at 20% (v/v) with four inorganic soil amendments and sphagnum peat in 30 cm of root-zone media.

Table 4. Peak concentration and percentage loss of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the effluent of sand amended with clinoptilolite zeolite and a porous ceramic at 1%, 5%, 10%, and 20% by volume.

Soil amendment	Rate (v/v)	$\text{NH}_4\text{-N}$		$\text{NO}_3\text{-N}$	
		Peak concn ($\text{mg}\cdot\text{L}^{-1}$)	Total loss (%)	Peak concn ($\text{mg}\cdot\text{L}^{-1}$)	Total Loss (%)
Nonamended	0	58.4	95.7	74.7	96.6
Clinoptilolite zeolite (CZ)	1	49.6 a ^z	75.0 a [*]	65.1 a	92.9 b
	5	39.1 a ^{***}	52.3 b [*]	64.3 a	98.8 a
	10	10.3 b ^{***}	17.0 c [*]	50.4 b ^{***}	96.9 ab
	20	4.3 b ^{***}	7.7 d [*]	48.9 b ^{***}	96.7 ab
Porous ceramic 1 (PC1)	1	52.3 a	78.7 a [*]	70.3 a	95.9
	5	25.4 b ^{***}	51.6 b [*]	57.7 ab	95.3
	10	11.4 c ^{***}	32.6 c [*]	54.6 ab [*]	96.0
	20	6.7 c ^{***}	22.4 d [*]	46.3 b ^{***}	96.3
Orthogonal contrasts					
CZ vs. PC1 1%		NS	NS	NS	NS
CZ vs. PC1 5%		NS	NS	NS	NS
CZ vs. PC1 10%		NS	NS	NS	NS
CZ vs. PC1 20%		*	***	NS	NS

^zMeans within columns for the same soil amendment followed by the same letter are not significantly different at $P = 0.05$ by Fisher's protected LSD. NS, *, ***, Nonsignificant or significant orthogonal contrasts at $P = 0.05$ or 0.001, respectively.

Table 5. Peak concentration and percentage loss of $\text{NH}_4\text{-N}$ and $\text{NO}_3\text{-N}$ in the effluent for sand amended with clinoptilolite zeolite and a porous ceramic at 10% (v/v) incorporated to 2.5, 15, and 30 cm depths.

Soil amendment	Depth (cm)	$\text{NH}_4\text{-N}$		$\text{NO}_3\text{-N}$	
		Peak concn ($\text{mg}\cdot\text{L}^{-1}$)	Total loss (%)	Peak concn ($\text{mg}\cdot\text{L}^{-1}$)	Total Loss (%)
Nonamended	0	61.9	97.6	74.6	97.9
Clinoptilolite zeolite (CZ)	2.5	30.7 a ^{***}	68.2 a [*]	46.0 a ^{**}	93.0 a
	15	20.1 ab ^{***}	38.2 b [*]	55.7 a	96.8
	30	10.4 b ^{***}	17.6 c [*]	49.4 a ^{**}	96.5 a
Porous ceramic 1 (PC1)	2.5	38.1 a ^{***}	76.6 a [*]	61.0 a	94.7 a
	15	19.9 b ^{***}	49.4 b [*]	54.6 a [*]	91.6 a
	30	11.4 c ^{***}	32.2 c [*]	53.1 a [*]	97.4 a
Orthogonal contrasts					
CZ vs. PC1 2.5 cm		***	NS	NS	NS
CZ vs. PC1 15 cm		NS	NS	NS	NS
CZ vs. PC1 30 cm		NS	*	NS	NS

^zMeans within columns for the same soil amendment followed by the same letter are not significantly different at $P = 0.05$ by Fisher's protected LSD. NS, *, **, ***, Nonsignificant or significant orthogonal contrasts at $P = 0.05$, 0.01, or 0.001, respectively.

ment incorporation depth resulted in stepwise reductions in $\text{NH}_4^+\text{-N}$ leaching (Table 5). Even incorporating these amendments to a rather shallow depth of 2.5 cm decreased cumulative $\text{NH}_4^+\text{-N}$ losses by almost 25%, and resulted in significantly lower peak $\text{NH}_4^+\text{-N}$ concentrations compared to nonamended sand. As expected, the higher CEC amendment resulted in the least $\text{NH}_4^+\text{-N}$ leaching loss.

EXPERIMENT 4. Fertilizer incubation time had no effect on either $\text{NH}_4^+\text{-N}$ or $\text{NO}_3^-\text{-N}$ leaching from nonamended or amended sands (data not presented). However, differences in $\text{NH}_4^+\text{-N}$ losses were observed between amendments, and these results were consistent with data from the previous experiments at this amendment incorporation rate. Less $\text{NH}_4^+\text{-N}$ leached in amended sands, with losses decreased by 73% to 87%, compared to the nonamended sand control.

Discussion

Nutrient movement and retention in nearly saturated or saturated soils can be described by a combination of three processes: convection, diffusion, and dispersion (Cameron and Haynes, 1986). Convection refers to solute transport due to mass flow of water along a hydraulic gradient. When there is an uneven distribution of solutes in the soil there is a diffusive flux of solutes from an area of high concentration to a zone of low concentration. In these experiments a relatively high concentration of N was applied to previously nonfertilized root-zone surfaces. Once the fertilizer N dissolved in the leaching solution, a concentration gradient formed and ion exchange occurred upon contact with available exchange sites. Additionally, the mechanical action of liquid flowing through the soil matrix results in mixing, which

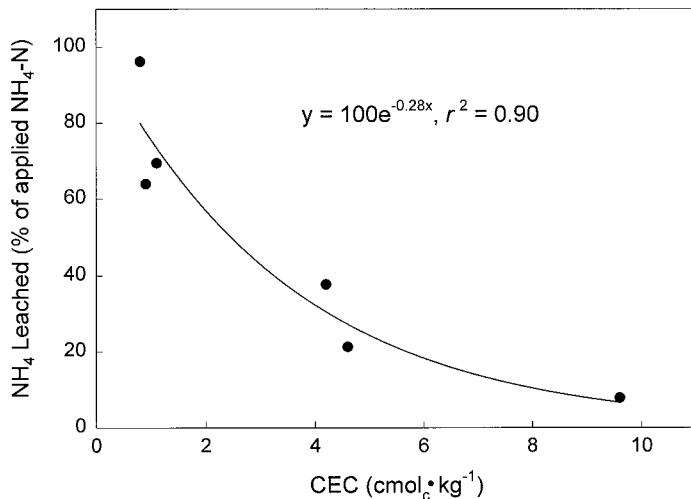


Fig. 2. Relationship between CEC of sand-based root-zone mixtures and percentage ammonium leached.

tends to equalize the solute distribution process and enhances the dispersive effects of diffusion. The mixing effect is influenced by several important factors: flow velocity, variation in pore size diameters, and the path length of pores (Hillel, 1982). In most soils, a variety of pore sizes are present which results in a range of pore velocities. In these coarse textured rootzones, the majority of the pores were rather large resulting in rapid percolation rates (Table 2). Further, though the path which solutes must travel can fluctuate greatly due to pore geometry and tortuosity affecting ion exchange, in these rootzones the N solution probably followed a relatively direct path. Together, these factors contributed to mixing of the soil solution with exchange sites which tended to promote maximum fixation.

Due to the rapid percolation rates of the rootzones, conditions for maximum surface cation exchange seemed present. Although mixing and surface exchange may have been optimal, it is also important to consider that the rapidly flowing N solution may have bypassed a rather substantial portion of the exchange sites which are located inside these porous inorganic amendments. Thus, rapid percolation rates of these mixtures which resulted in predominantly macropore flow may have actually decreased the potential effectiveness of these soil amendments. The two most effective inorganic amendments, CZ and PC1, have rather high inherent CECs and results of the experiments indicate that the primary mode of exchange appeared to be surface exchange, with the internal exchange sites not being utilized much if any. This is supported by results from Expt. 2, the amendment rate study. Had the internal exchange sites been utilized, the decrease in NH₄⁺-N leaching should have been an additive response with maximum NH₄⁺-N fixation or retention occurring at the 5% incorporation rate. This rate is based on total charge balance between the theoretical number of available exchange sites and the quantity of charge added from the NH₄⁺-N fertilizer solution.

To investigate the potential for N diffusion in sand amended with CZ or PC1, Expt. 4, the incubation study, was conducted. In this experiment incubation time had no effect on NH₄⁺-N leaching, which may have been due to the 20% (v/v) amendment rate used which contributed sufficient exchange sites to retain the NH₄⁺ charge addition. However, no amendment or incubation time resulted in zero NH₄⁺-N leaching, which suggests an interesting consideration that perhaps the internal exchange sites of

these amendments may not be utilized. This is particularly true for the CZ product which has a very high theoretical CEC, >185 cmol_c•kg⁻¹, but was similar to PC1 which has a lower CEC. Therefore, in rootzones constructed with these materials, surface exchange sites may be more important than total CEC with regards to NH₄⁺-N retention and leaching.

Regardless of whether cation exchange occurred externally or internally, regression analysis demonstrated that the CEC of the root-zone mixtures was the primary determinant for NH₄⁺-N leaching (Fig. 2) and the physical properties of these root-zone mixtures were not significant (data not presented). As CEC of the root-zone mixtures increased, NH₄⁺-N losses significantly decreased ($R^2=0.90$, $P<0.05$). This attraction to negatively charged exchange sites of CZ, peat, and PC1, is consistent with previous research for this well known exchange mechanism (Talibudeen, 1981; Thomas, 1977). This process is reversible with the NH₄⁺ in soil solution being in dynamic equilibrium with that held on exchange sites, and exchangeable NH₄⁺-N may also become readily available to turfgrasses after oxidation by nitrifying bacteria (Sylvia et al., 1997). Furthermore, the higher affinity of the porous ceramic, PC1, for NH₄⁺-N compared to the diatomaceous earth product is consistent with previous research regarding similar inorganic amendments (McCoy and Stehouwer, 1998). Additionally, our results regarding decreased NH₄⁺-N leaching with increasing CZ incorporation rates is consistent with similar studies by MacKown and Tucker (1985).

Concentrations of NO₃⁻-N in the effluent ranging from 30 to 80 mg•L⁻¹ are consistent with values reported previously for NO₃⁻-N movement in sandy soils (Mancino and Troll, 1990). Additionally, although NH₄⁺-N may be protected from leaching, previous research found that significant NO₃⁻-N leached from a sandy medium amended with zeolite and fertilized with ammonium sulfate (Huang and Petrovic, 1994; Perrin et al., 1998). Therefore, caution regarding timing of N applications to coincide with plant uptake may be necessary. Huang and Petrovic (1994) reported that large NO₃⁻-N losses occurred following application of N at 293 kg•ha⁻¹ to a nonamended sand but that addition of zeolite to sand significantly decreased NO₃⁻-N concentrations, with leachate levels consistently <10 mg NO₃⁻-N/L. However, their experimental system included creeping bentgrass turf, and it is possible that zeolite affected NO₃⁻-N leaching by improving the root-zone physical properties and consequently promoting deeper and more extensive rooting.

Poor retention of NO₃⁻-N in this experimental system was most likely due to anion exclusion. Under normal conditions where electroneutrality is maintained between the soil surface and cations in the soil solution, electrostatic repulsion of anions occurs. Further, in coarse textured soils like those commonly used for putting greens, over half of the water movement in the rootzone is through the macropore system (Quisenberry and Phillips, 1976; Thomas et al., 1978). This may result in rapid NO₃⁻ leaching in percolating waters and little if any opportunity for NO₃⁻ to be retained or removed.

In conclusion, these experiments document that NH₄⁺-N leaching is high in nonamended quartz sands, exceeding 95% of applied N. However, NH₄⁺-N leaching losses can be decreased substantially to ≤8%, by incorporating certain inorganic amendments and to a lesser extent, sphagnum peat provided these amendments have sufficient CEC. Nitrate leaching continues to be a concern in sand-based putting green media, particularly during turfgrass establishment when root systems are shallow, and when soluble fertilizers are used. Therefore, a potential

rootzone media/N management system to minimize NO_3^- -N leaching on sand-based rootzones may consist of amending sands with peat and/or CZ or a relatively high CEC porous ceramic and at least initially employing an NH_4^+ -N based fertilizer program. This system would provide a rooting medium which consists of adequate but not excessive percolation and the added benefit of sufficient nutrient exchange sites which would retain N in the rooting medium where it could be utilized by turfgrasses. Future research of anion exchange products that increase the anion exchange capacity of sand-based rootzone mixtures may limit NO_3^- leaching with similar results to the CEC enhancing soil amendments in these experiments.

Literature Cited

- Beard, J.B. 1982. Turf management for golf courses. MacMillan, New York.
- Blake, G.R. and K.H. Hartge. 1986. Particle density, p. 377–382. In: A. Klute (ed.). Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. Amer. Soc. Agron.–Soil Sci. Soc. Amer., Madison, Wis.
- Bowman, D.C., D.A. Devitt, T.W. Ruffy, Jr., and M.C. Engelke. 1998. Root architecture affects nitrate leaching from bentgrass turf. *Crop. Sci.* 38:1633–1639.
- Brauen, S. and G. Stahnke. 1995. Leaching of nitrate from sand putting greens. *U.S. Golf Assn. Green Section Record.* 33(1):29–32.
- Brown, K.W., J.C. Thomas, and R.L. Duble. 1982. Nitrogen source effect on nitrate and ammonium leaching and runoff losses from greens. *Agron. J.* 74:947–950.
- Cameron, K.C. and R.J. Haynes. 1986. Retention and movement of nitrogen in soils. In: Mineral nitrogen in the plant–soil system, p. 166–241. R.J. Haynes (ed.). Academic Press, Inc., Orlando, Fla.
- Carlson, R.M. 1986. Continuous flow reduction of nitrate to ammonia with granular zinc. *Anal. Chem.* 58:1590–1591.
- Danielson, R.E. and P.L. Sutherland. 1986. Porosity, p. 443–462. In: A. Klute (ed.). Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. Amer. Soc. Agron.–Soil Sci. Soc. Amer., Madison, Wis.
- Ferguson, G.A. and I.L. Pepper. 1987. Ammonium retention in sand amended with clinoptilolite. *Soil Sci. Soc. Amer. J.* 51:231–234.
- Hillel, D. 1982. Introduction to soil physics. Academic Press, Inc., San Diego, Calif.
- Huang, Z.T. and A.M. Petrovic. 1994. Clinoptilolite influence on nitrate leaching and nitrogen use efficiency in simulated sand based golf greens. *J. Environ. Qual.* 23:1190–1194.
- Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods, p. 687–734. In: A. Klute (ed.). Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. Amer. Soc. Agron.–Soil Sci. Soc. Amer., Madison, Wis.
- MacKown, C.T. and T.C. Tucker. 1985. Ammonium nitrogen movement in a coarse-textured soil amended with zeolite. *Soil Sci. Soc. Amer. J.* 49:235–238.
- Mancino, C.F. and J. Troll. 1990. Nitrate and ammonium leaching losses from N fertilizers applied to ‘Penncross’ creeping bentgrass. *Hort-Science* 25:194–196
- McCoy, E.L. and R.C. Stehouwer. 1998. Water and nutrient retention properties of internally porous inorganic amendments in high sand content rootzones. *J. Turf. Mgmt.* 2(4):49–69.
- Miltner, E.D., B.E. Branham, E.A. Paul, and P.E. Rieke. 1996. Leaching and mass balance of ^{15}N -labeled urea applied to Kentucky bluegrass turf. *Crop Sci.* 36:1427–1433
- Ming, D.W. and F.A. Mumpton. 1989. Zeolites in soils, p. 874–911. In: J.B. Dixon and S.B. Weed (eds.). Minerals in soil environments. 2nd ed. Soil Sci. Soc. Amer., Madison, Wis.
- Nus, J.L. and S.E. Brauen. 1991. Clinoptilolitic zeolite as an amendment for establishment of creeping bentgrass on sandy media. *HortScience* 26:117–119.
- Perrin, T.S., J.L. Boettinger, D.T. Drost, and J.M. Norton. 1998. Decreasing nitrogen leaching from sandy soil with ammonium-loaded clinoptilolite. *J. Environ. Qual.* 27:656–663.
- Quisenberry, V.L. and R.E. Phillips. 1976. Percolation of surface applied water in the field. *Soil Sci. Soc. Amer. J.* 40:484–489.
- SAS Inst., Inc. 1996. SAS user’s guide: Statistics version 6.11. SAS Inst., Inc., Cary, N.C.
- Steel, R.G.D, J.H. Torrie, and D.A. Dickey. 1997. Principles and procedures of statistics: A biometrical approach. 3rd ed. McGraw-Hill, Inc. New York.
- Sylvia, D.M., J.J. Fuhrman, P.G. Hartel, and D.A. Zuberer. 1997. Principles and applications of soil microbiology. Prentice-Hall, Inc., Englewood Cliffs, N.J.
- Talibudeen, O. 1981. Cation exchange in soils, p. 115–177. In: D.J. Greenland and M.H.B. Hayes (eds.). The chemistry of soil processes. Wiley, New York.
- Thomas, G.W. 1977. Historical developments in soil chemistry: Ion exchange. *Soil Sci. Soc. Amer. J.* 41:230–238.
- Thomas, G.W., R.E. Phillips, and V.L. Quisenberry. 1978. Characterization of water displacement in soils using simple chromatographic theory. *Soil Sci.* 29:32–37.
- United States Golf Association (USGA), 1993. USGA recommendations for a method of putting green construction. *U.S. Golf Assn. Green Section Record* 31(2):1–33.