Goat Urine and Limestone Affect Nitrogen and Cation Distributions in an Acidic Grassland

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Prior surface application of limestone may influence soil changes resulting from high rates of urine deposition occurring where goats (Capra aegagrus hircus L.) congregate. A quantity of limestone equivalent to 0 and 6720 kg ha\(^{-1}\) was surface applied to vegetated 45-cm-deep columns of a Typic Hapludult soil collected from an abandoned Fescue spp. grassland in southern West Virginia. Eighteen weeks after lime application, one, two, or three applications of urine supplying a total of 36, 98, or 177 g m\(^{-2}\) of N, respectively, were made. One and two applications of urine increased vegetative growth and decreased the amount of water leaching through the column, but the third addition damaged plants. The three-addition treatment reduced the amount of N taken up by the plants, decreased transpiration, increased leachate volume, and resulted in a 12-fold increase in the amount of N leached from the columns compared with the one-application treatment. Leachate Ca, Mg, and K were increased by urine. Soil pH and extractable Ca and Mg were decreased by urine and increased by limestone, and extractable Al was increased by urine and decreased by limestone applications. Net amounts of N recovered as NH\(_3\) gas released to the atmosphere, N taken up into aboveground plant material, NH\(_4^+\) and NO\(_3^-\) extracted from soil, and NH\(_4^+\) and NO\(_3^-\) in drainage water ranged from 49 to 77% of the amount added. Surface application of limestone alleviated some of the detrimental effects of high rates of urine addition by increasing levels of pH, Ca, and Mg and reducing Al as deep as 28 cm in the profile.

Abbreviations: EC, electrical conductivity; pH\(_s\), pH in 0.01 mol L\(^{-1}\) CaCl\(_2\).

Production of chevon (goat meat) in the United States is considerably less than the amount consumed, and the shortfall is made up by imports (Singh-Knights and Knights, 2005). The northeastern consumer market is an important one, yet much of the American goat meat supplied to this market comes from the south-central United States. The Appalachian region lies close to the market area and contains small farms with abandoned pastures and woodlots where production of meat goats is feasible. Goats are often used to clear brush and weeds where herbicide use is not appropriate.

The major nitrogenous component of small ruminant urine is urea, with smaller amounts of creatine, allantoin, and hippuric acid (Whitehead, 1995); the most abundant cation is K\(^+\). When urea contacts soil, the enzyme urease facilitates its hydrolysis to NH\(_4^+\) and either HCO\(_3^-\) (at pH of 6.3 or higher) or CO\(_2\) and H\(_2\)O at lower pH (Whitehead, 1995). Both of these reactions consume H\(^+\) ions, and can raise soil pH by up to two to three units. At high pH, NH\(_4^+\) can convert to NH\(_3\) gas, which may be lost to the atmosphere through volatilization. Ammonium can be nitrified through conversion to NO\(_3^-\) and then to NO\(_2^-\) (Lovell and Jarvis, 1996), usually through the actions of soil microbes. Both of these processes liberate H\(^+\) ions, lowering pH, thus reversing the increase in pH resulting from hydrolysis. Nitrification is usually somewhat inhibited by low pH and low concentrations of plant nutrients (Brady, 1990). Under anaerobic conditions, such as found in saturated soil in the presence of microbe-available C sources, NO\(_3^-\) can be denitrified to N\(_2\)O and N\(_2\) (Clough et al., 2004).

Retention and uptake of the various forms of N varies. In soils of temperate climates with a predominance of cation exchange capacity (CEC) over anion exchange capacity, NH\(_4^+\) is usually well retained on the soil complex, but if the amounts produced are greater than the CEC, NH\(_4^+\) is subject to leaching. Urea and NO\(_3^-\) are both more easily leached than NH\(_4^+\).

Reactions in dystrophic, acidic soils typical of abandoned grasslands and woodlots in the Appalachian region may be different than in limed, active pastures. Microbial populations (and subsequently, microbial transformations of urine) in pastures that have been abandoned for a long time are not necessarily the same as those of fertilized pastures that are frequently clipped (Williams et al., 2003).

Because of the social behavior of goats, even moderate stocking rates can result in areas of high rates of dung and urine deposition. Where high stocking densities occur (rotational grazing at 125 goats ha\(^{-1}\) for 9 d, or mob grazing for brush clearing at 200 goats ha\(^{-1}\) for 9 d), an estimated 2 or 3% of urine patches will overlap according to probability calculations based on uniform spatial distributions of 20 daily deposits of 0.04-m\(^2\) area.
Overlapping at these stocking densities will be much greater where goats congregate (salt block, water, and shade locations). On the other hand, soil compaction resulting from concentrated hoof action can increase soil density, decrease aeration, and promote denitrification, thus reducing the potential for leaching of NO$_3^−$.

Under conditions where multiple applications of urine occur, concentrations of salts and hormones from the urine and concentrations of toxic NH$_3$ can cause scorching, which can damage or destroy vegetation (Williams et al., 1999). Decreased plant growth interferes with the buffering system usually functioning under normal conditions. Under conditions of moderate N addition where urine deposits are isolated from each other and are not contiguous, plants respond to increased N concentrations by increasing their growth and uptake of N, thus decreasing the amount of N subject to leaching. If urine concentrations become high due to contiguous or overlapping deposits and plant health is compromised, the buffering mechanism is less effective; this can result in large amounts of NO$_3^−$ moving below the rooting zone into groundwater. Water for human consumption in nearby wells can become contaminated with NO$_3^−$, which can increase the incidence of methemoglobinemia, a serious health hazard to infants (Fan et al., 1987). Groundwater contamination can also cause eutrophication of streams and ponds. In addition to possible contamination concerns, concentrated urine applications can decrease soil Ca and Mg concentrations as cations are displaced from the exchange complex by NH$_4^+$ and leached out with NO$_3^−$ (Fox, 2004).

One of the management tools available to farmers for improving grassland productivity is the surface application of limestone, but due to the low solubility of CaCO$_3$, neutralization of toxic Al in the rooting zone can take several years (Ritchey et al., 2004). Given the slowness of the reaction of limestone, it would be useful to apply limestone as early as possible. On the other hand, application of limestone to brush-infested abandoned pastures is more difficult than application after goats have removed aboveground biomass. Little is known about the combined effects of surface liming and heavy urine applications to dystrophic soils. We hypothesized that under conditions of high salt concentrations and fluctuations in pH associated with hydrolysis and nitrification of large quantities of added urine, surface limestone applications may raise pH and increase Ca and Mg concentrations in the rooting zone while reducing Al concentrations, resulting in greater dry matter productivity.

This study was initiated to investigate the effects of medium to high rates of urine application on the fate of N in a dystrophic abandoned pasture soil and to measure the effects of surface application of limestone on N transformations, N movement, and changes in cation status.

**MATERIALS AND METHODS**

Gaseous NH$_3$ production resulting from urine additions to soil columns was described in a previously (Ritchey et al., 2003), and the present investigation describes additional aspects of the same experiment.

Briefly, 32 vegetated soil macrocosms were collected in early August 2000 from an abandoned grassland site in southern West Virginia (37°40′ N, 80°7′ W) on a soil complex consisting of Gilpin (fine-loamy, mixed, mesic Typic Hapludult) and Lily (fine-loamy, siltaceous, mesic Typic Hapludult) series by driving sharpened polyvinyl chloride cylinders into the profile. Vegetation on the 45-cm-deep columns (inside diameter 15.2 cm) varied and consisted mainly of fescue (Festuca spp.) and nine broadleaf species.

To provide drainage from the columns, a 290-cm-long fiberglass wick 6 mm in diameter (American Seal and Packing, Mountain Valley, CA) was prepared by baking 4 h at 400°C to remove hydrocarbons, then washing in distilled water until the liquid rinsate was clear (Knutson et al., 1993). The wick was arranged in a coil in contact with the soil at the bottom of the column and the rest of the wick extended 76 cm below the bottom soil surface. The wick was encased in a flexible plastic tube (inside diameter 13 mm) that was covered with aluminum foil to reduce algal growth. Leachate was collected three times per week and pooled to provide one sample per column per week. A representative subsample was stored at −20°C.

Columns were acclimated for 10 wk in a greenhouse and vegetation was periodically clipped to 5-cm height. Greenhouse temperatures ranged from 7 to 32°C, and water was added to the columns sufficient to maintain water movement through the soil profile. Beginning 15 Oct. 2000, instead of distilled water, columns were hydrated with simulated acid rain (pH 5) formulated by adding to 100 L distilled water the following: 17.6 mg NaCl, 70.9 mg CaSO$_4$·2H$_2$O, 35.5 mg MgSO$_4$·7H$_2$O, 6.9 mg K$_2$SO$_4$, 36.8 mg NaNO$_3$, 74.6 mg (NH$_4$)$_2$SO$_4$, 24.3 mg NH$_4$NO$_3$, 0.84 mg H$_2$PO$_4$, 38.3 mg H$_2$SO$_4$, and 22.1 mg HNO$_3$ (Halverson and Gentry, 1990).

On 10 Oct. 2000, 16 of the columns received a surface application of 12.3 g of agricultural limestone to provide a rate of 6720 kg ha$^{-1}$. The limestone contained 43% MgCO$_3$ and 54% CaCO$_3$, with 104% CaCO$_3$ equivalence and 98% effective neutralizing value. The limestone particle size was such that 100% passed a 0.84-mm (20 mesh) screen, 90% passed 0.3 mm (50 mesh), 80% passed 0.25 mm (60 mesh), and 75% passed 0.15 mm (100 mesh).

Three batches (A, B, and C) of urine were collected from three goat weathers as described by Ritchey et al. (2003). The urine was stored at −20°C. On 12 February (18 wk after limestone application), 100 mL of urine (Urine A) was added to the surface of each of the limed (L) and unlimed (U) columns excluding controls, which received 100 mL of distilled water (Table 1). Immediately after the first urine application, domes of translucent plastic were placed onto the top of each column to measure the release of NH$_4$ from the soil during a 1-wk period as air was pumped through the dome at approximately 60 L h$^{-1}$ as described.

<table>
<thead>
<tr>
<th>Table 1. Amounts of agricultural limestone and N and K (as goat urine) surface applied to columns of soil taken from an abandoned acidic, dystrophic Appalachian grassland.</th>
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</thead>
<tbody>
<tr>
<td><strong>Treatment</strong></td>
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<td>0U</td>
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<tr>
<td>3L</td>
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<tr>
<td>3U</td>
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<tr>
<td>3L</td>
</tr>
</tbody>
</table>

† Treatment 1 received 100 mL of Urine A on 12 Feb. containing 6.5 g L$^{-1}$ N and 1.82 g L$^{-1}$ K. Treatment 2 received, in addition to Urine A, 100 mL of Urine B on 26 Feb. containing 11.2 g L$^{-1}$ N and 5.27 g L$^{-1}$ K. Treatment 3 received, in addition to Urines A and B, 100 mL of Urine C on 3 Mar. containing 14.4 g L$^{-1}$ N and 5.8 g L$^{-1}$ K.
by Ritchey et al. (2003). On 26 February, 16 columns that had received the first application were retreated with 100 mL of Urine B. On 12 March, eight of the columns that had received both the first and second applications were treated with 100 mL of Urine C. Ammonia generation was measured on all 32 columns following the second and third applications. Treatments receiving zero, one, two, or three applications were designated as 0, 1, 2, and 3, respectively.

During the 4-wk period after the last application of urine, weekly additions of artificial acid rain averaged 350 mL. The rain was added in small doses several times per day three times per week to avoid ponding and minimize preferential flow. For the next 12 wk, an average of 755 mL of water was added weekly. During the last 5 wk of the experiment, the columns received 900 mL of water per week. This pattern of addition was chosen to simulate common patterns of water movement through pastures of the central part of the eastern United States where there is low or no net leaching in the summer when rates of evaporation and water utilization by plants are high, and major downward movement occurs in late winter and early spring (Guillad and Kopp, 2004).

Soil solution samples from the treatments receiving one and three applications of urine were collected one to three times per week using 10-cm Rhizon samplers of 2-mm diameter (Ben Meadows Co., Janesville, WI) inserted into the columns at depths of 2.7, 5.4, 10.8, 21.6, and 43.2 cm.

Plant material was harvested to 5-cm height nine times from 3 May to 17 August. At the end of the experiment (21–24 Aug, 2001), vegetation was harvested down to the soil surface. The vegetation was oven dried (67°C) and weighed for evaluation of dry matter production.

To collect soil samples, the columns were laid in a horizontal position and a lengthwise saw cut was made on each side of the column. One-half of the pipe was removed so that the soil in the column could be sectioned with minimum contamination. The columns were sectioned at depths of 1.6, 4, 7, 10, 16, 22, 28, 34, and 40 cm. Samples for measurement of moisture content and NO$_3^-$ and NH$_4^+$ concentration were collected immediately and extracted with 2 mol L$^{-1}$ KCl (Keeney and Nelson, 1982). The extract was analyzed by flow injection analyzer (Alpkem RFA/2 Asia-Paciﬁc International, Clackamas, OR). No effort was made to separate NO$_3^-$ and NO$_2^-$, and because NO$_2^-$ was probably small relative to NO$_3^-$, the values are reported as NO$_3^-$ for the sake of simpliﬁcation. The remaining soil was air dried and weighed for bulk density determination and analyzed for neutral 1 mol L$^{-1}$ NH$_4$OAc-extractable Ca, Mg, and K (Thomas, 1982) and for 1 mol L$^{-1}$ KCl-extractable AI (Barnhisel and Bertsch, 1982) by inductively coupled plasma (ICP)–atomic emission spectrometry (HORIBA Jobin Yvon, Edison, NJ). Soil electrical conductivity (EC) was measured in a 1:1 soil/water suspension. Soil pH was measured using 1:1 soil/0.01 mol L$^{-1}$ CaCl$_2$ (pH$_7$). Leachate and soil solution NO$_3^-$–N and NH$_4^+$–N were determined using suppressed ion chromatography (Dionex Corp., Sunnyvale, CA).

Subsamples of urine collected at the time of application and stored at ~20°C were analyzed about 6 mo after application for K concentration by ICP. The samples were refrozen and reanalyzed on 19 Nov. 2004 for total dissolved N using a Shimadzu TOC-V CPN Total Organic Analyzer, with TNM-1 Total Nitrogen Measuring Unit (Shimadzu Scientific Instruments, Columbia, MD).

Plant material was analyzed for N by Carlo Erba Elemental Analyzer Model EA1108 (CE Elantech, Lakewood, NJ).

Data Analysis

Columns were arranged in the greenhouse in a randomized complete block design. All treatments were replicated four times, but one of the limed columns that received three applications was excluded from statistical analysis due to the appearance of urine in the column leachate, indicating excessive macropore flow.

Analysis of variance and regression evaluations were conducted using general linear model statistical procedures (SAS Institute, 1990). For separation of means, F test protected LSD values (Steel and Torrie, 1980) are given. Treatment differences were considered significant at $P \leq 0.05$. Factorial analysis was used to identify the effects of urine and lime on distributions of soil parameters where lime × urine interactions were generally not statistically significant.

RESULTS AND DISCUSSION

Urine Nutrient Concentration, Plant Growth, and Plant Nitrogen Concentration

The concentrations of N and K in the urine varied (Table 1). Urine B was considerably more concentrated than Urine A, and slightly less concentrated than Urine C. The values of N measured in the urine subsamples were higher than the values reported previously by Ritchey et al. (2003), and are thought to be more accurate because we used a more appropriate technique for the reanalysis. The amount of N applied in the first application (36 g m$^{-2}$ or 360 kg ha$^{-1}$) was similar to the amount of N that might be applied to a high-yielding maize (Zea mays L.) crop. Treatments that received all three urine applications (such as would occur in areas where goats congregate) received almost five times more N than the single-application treatments.

The treatments receiving one urine application produced almost three times as much dry matter (DM) as the treatments with no added urine, and mean production in the treatments that received two urine applications was more than 4.5 times the production in the treatments with no urine (Table 2). Vegetative growth presumably responded to the increased availability of N and K present in the goat urine. Lime addition to the zero-urine treatment had little effect on DM, but in the one and two urine application treatments there was a tendency for surface lime addition to increase yields (Table 2). Liming decreased DM at the high-N rate, probably because it increased NH$_3$ concentration in the collection domes and exacerbated scorching damage, as discussed by Ritchey et al. (2003). In the undamaged treatments, the range of productivity that we measured (153–850 g m$^{-2}$) is consistent with values found in abandoned and restored grasslands of the eastern United States (Stinner et al., 1984; Ritchey et al., 2004).

The mean concentration of N in DM without added urine was 17 g kg$^{-1}$. This compares with about 12 g kg$^{-1}$ of N found in old field growth in the Georgia Piedmont by Stinner et al. (1984). In the treatments receiving one, two, and three applications of urine, mean N concentrations in DM were 26.2, 35.8, and 31.3 g kg$^{-1}$, respectively. Increased productivity and increased N concentration in the DM with the first and second urine additions resulted in greatly increased N uptake by vegetation (Table 2). Nitrogen uptake in the limed two-application treatment was 6 g m$^{-2}$ per month.

Amount of Leachate

The amount of water added to the columns from the time of the first urine treatment until harvest 27 wk later was 16.1 L (886 mm), equivalent to 85% of mean annual rainfall in southern West Virginia. The volume of leachate collected was low-
est in the two-application treatment (164 mm or 18% of added water) and greatest in the three-application treatment (378 mm or 43% of added water). In comparison, in pastures in central Pennsylvania, Jabro et al. (1998) recovered 27% of annual precipitation as percolation flow-through and Zhu et al. (2002) recovered 52% of precipitation as percolate.

A major factor affecting the variation in the amount of percolation was the amount of plant growth. Leachate volume between 3 May and 18 August (the period of highest insolation) was negatively correlated with the amount of vegetative dry matter harvested from the columns during the same interval (Fig. 1). The flow-through volume during this period was lowest in the treatments where the amount of plant growth was highest (2L). Liu et al. (1997) stated that under conditions of similar soil and water inputs, differences in water use by vegetation could cause differences in percolation, and this is clearly evident in the present experiment. The decreased vegetation in the high-urine treatments due to scorching damage presumably lowered transpiration and increased the mean rate of flow-through. Such higher percolation rates would be expected to exacerbate the potential for detrimental leaching of N into groundwater.

### Soil Solution Concentrations

Because of high variability in the determinations, mean values of inorganic NH₄⁺ and NO₃⁻ in soil solution were pooled to five time periods and depths of 4 cm (mean concentrations obtained from lysimeters at 2.7 and 5.4 cm), 16 cm (mean readings at 10.8 and 21.6 cm), and 43 cm (mean readings at 43 cm). Partly due to high variability, no statistically significant effects of lime addition were detected.

The peak mean NH₄⁺ concentration at 4 cm in the treatment receiving one urine application was 21 mg L⁻¹, occurring during the first 8-wk period (data not shown). Concentrations were <6 mg L⁻¹ in the other depths and time periods. In the treatment receiving three applications, the 4-cm depth had a mean peak concentration of 186 mg L⁻¹ occurring at 9 to 11 wk; the concentration at the 16-cm depth peaked at 107 mg L⁻¹ at 12 to 15 wk; and at the 43-cm depth, a peak of 78 mg L⁻¹ was observed at 20 to 29 wk. The decline in NH₄⁺ concentration with depth indicated a transformation of NH₄⁺ to NO₃⁻ as N moved down through the columns.

Mean NO₃⁻ concentration (data not shown) was <2 mg L⁻¹ at the 4-cm depth in the one-application treatment (indicating that not much NH₄⁺ had nitrified while N was in the surface layer of the column), but a peak of 37 mg L⁻¹ was observed at the 16-cm depth at 9 to 11 wk. The concentration of NO₃⁻ at the 43-cm depth (26 mg L⁻¹) was apparently still increasing during the last 9 wk of the experiment. In the treatment receiving three applications, the NO₃⁻ concentration at the 4-cm depth peaked at 136 mg L⁻¹ at 12 to 15 wk, and the NO₃⁻ concentration at the 16-cm depth peaked at 213 mg L⁻¹ at 16 to 19 wk. At the 43-cm depth, the highest concentration (203 mg L⁻¹) was found during the last 9 wk, and was probably still increasing.

### Leachate Concentrations

**Ammonium**

Leachate N concentrations were less variable than those measured in soil solution samples, probably because the samples represented a larger volume of soil. Mean leachate NH₄⁺ concentrations (Fig. 2) in treatments receiving one and two urine applications tended to be slightly higher than in the control, but they were still generally low (<8 mg L⁻¹). In the three-application treatment, mean concentrations reached

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**Table 2. Dry matter (DM) production and recovery of N added as four concentrations of goat urine (zero, one, two, or three applications) to an abandoned acidic, dystrophic Appalachian grassland soil that received (L) or did not receive (U) surface application of limestone. Values for volatilized NH₃–N are taken from Ritchey et al. (2003).**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>DM production (g m⁻²)</th>
<th>N added (g m⁻²)</th>
<th>NH₃ volatilized (g m⁻²)</th>
<th>NH₄⁺ (g m⁻²)</th>
<th>NO₃⁻ (g m⁻²)</th>
<th>NH₄⁺ + NO₃⁻ (g m⁻²)</th>
<th>Soil recovery</th>
<th>Leachate recovery</th>
<th>Sum (g m⁻²)</th>
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</thead>
<tbody>
<tr>
<td>0U</td>
<td>186</td>
<td>0</td>
<td>0.18 c</td>
<td>1.9 b</td>
<td>0.3 d</td>
<td>0.01 b</td>
<td>0.1 c</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>0L</td>
<td>153 e</td>
<td>0</td>
<td>0.19 c</td>
<td>4.1 e</td>
<td>2.3 b</td>
<td>0.2 d</td>
<td>0.01 b</td>
<td>6.9</td>
<td></td>
</tr>
<tr>
<td>1U</td>
<td>409 cd</td>
<td>36</td>
<td>0.19 c</td>
<td>16.5 cd</td>
<td>2.0 b</td>
<td>0.4 d</td>
<td>0.5 b</td>
<td>24.4</td>
<td></td>
</tr>
<tr>
<td>1L</td>
<td>561 bc</td>
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<td>0.36 c</td>
<td>20.3 c</td>
<td>2.2 b</td>
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<td>0.5 b</td>
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<tr>
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<td>0.95 c</td>
<td>33.9 b</td>
<td>3.4 b</td>
<td>19.2 bc</td>
<td>0.6 b</td>
<td>72.1</td>
<td></td>
</tr>
<tr>
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<td>850 a</td>
<td>98</td>
<td>1.71 c</td>
<td>42.3 a</td>
<td>2.4 b</td>
<td>15.3 c</td>
<td>0.9 b</td>
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<tr>
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<td>177</td>
<td>8.3 b</td>
<td>19.9 c</td>
<td>10.0 a</td>
<td>28.9 a</td>
<td>18.9 a</td>
<td>50.2 a</td>
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</tr>
<tr>
<td>3L</td>
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<td>177</td>
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<td>11.2 de</td>
<td>4.2 b</td>
<td>25.6 ab</td>
<td>18.3 a</td>
<td>43.6 a</td>
<td>123</td>
</tr>
</tbody>
</table>

† Values within columns followed by the same letter are not significantly different at P ≤ 0.05.

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Fig. 1. Volume of leachate collected between 3 May and 18 August as related to the amount of dry matter produced during the same period in limed (L) and unlimed (U) vegetated soil columns taken from an acidic Typic Hapludult grassland.
mean concentrations had declined to about 32 mg L\(^{-1}\) by Week 28 when the experiment was terminated, indicating that the bulk of the soil solution NH\(_4^+\) had leached out of the column by the end of 28 wk. The total amount of NH\(_4^+\)–N that leached from the three-application treatment was about 25 times greater than the amount that leached from the two-application treatment. The mean volume of leachate from the three-application treatment was more than twice as great as from the two-application treatment (because of the smaller amount of vegetation), and this may have carried some NH\(_4^+\) out of the columns before it had time to be nitrified.

**Nitrate**

Mean leachate NO\(_3^-\)–N concentrations (Fig. 3) were higher than leachate NH\(_4^+\)–N concentrations. Even the treatment receiving only one urine application showed a peak concentration of about 45 mg L\(^{-1}\), and concentrations >10 mg L\(^{-1}\) (the regulatory limit for NO\(_3^-\)–N in drinking water) were observed from Weeks 14 to 24. In the three-application treatment, mean NO\(_3^-\)–N concentrations reached about 170 mg L\(^{-1}\).

The three-application NO\(_3^-\) peak occurred about 11 wk later than the NH\(_4^+\) peak, as would be expected because the NO\(_3^-\) was produced by oxidation of NH\(_4^+\).

**Calcium, Magnesium, and Potassium**

Lime did not have a significant effect on the total amounts of Ca, Mg, and K present in the leachate (data not shown). There was a marked effect of amount of urine applied. Total amounts of Ca, Mg, and K leached were each <1 g m\(^{-2}\) in the zero-urine treatment. The total amounts present in the leachate for the three-application treatment were 13.7 g m\(^{-2}\) Ca, 3.26 g m\(^{-2}\) Mg, and 11.6 g m\(^{-2}\) K.

The higher concentrations of K found in the leachate at high application rates were probably due to the K contained in the added urine. Higher concentrations of Ca may have originated from stripping of Ca from the soil exchange complex by high concentrations of NH\(_4^+\) and NO\(_3^-\) in the high-application treatments. The higher concentrations of Mg in the limed high-urine treatment leachates probably originated from Mg present in the limestone.

**Concentrations of Extractable Ions Remaining in the Soil Columns**

**Ammonium**

In the columns not receiving urine, concentrations of KCl-extractable NH\(_4^+\)–N (Fig. 4) averaged 13 mg kg\(^{-1}\) in the surface 0- to 1.6-cm layer, 6 mg kg\(^{-1}\) in the 1.6- to 4.3-cm layer, and 4 to 3 mg kg\(^{-1}\) in the deeper layers. There was no statistically significant effect of limestone addition on NH\(_4^+\) concentrations in the zero-urine treatment.

The treatments receiving three urine applications tended to have more extractable NH\(_4^+\)–N in the lower horizons than the other treatments. In addition to exchangeable NH\(_4^+\), some of the NH\(_4^+\) extracted by KCl may have been NH\(_4^+\) contained in soil solution that was still moving through the column. Due to decreased transpiration, the soil in the three-application treatment may have been more saturated, reducing the amount of O\(_2\) available to nitrify NH\(_4^+\), and this could help explain
the high NH$_4^+$–N concentrations observed. It is also possible that more NH$_4^+$ was present than the existing population of nitrifying microbes could transform to NO$_3^−$.

There was a significant effect of liming in the columns that received three urine applications. In the 28- to 40-cm layers, the limed treatment had less residual NH$_4^+$ than the unlimed treatment, and liming in the three-application treatment caused an overall decrease in recovered N of 13 g m$^{-2}$ (Table 2).

**Nitrate**

In the treatments not receiving urine or receiving just one urine application, little KCl-extractable NO$_3^−$ was present (Fig. 5). The 0- to 1.6-cm layer had about 1 mg kg$^{-1}$, and in the other layers the mean concentrations were generally <0.5 mg kg$^{-1}$. There was no effect of surface lime application on extractable NO$_3^−$–N in the zero-urine treatments.

Where two or three applications of urine were made, the concentrations of extractable NO$_3^−$–N in the layers below 10 cm were markedly higher than in treatments receiving zero or one application. In these treatments, not all of the mobile NO$_3^−$–N had leached out of the columns (Fig. 3). There was a tendency for the limed two- and three-application treatments to have less NO$_3^−$ than the respective unlimed treatments. In the two-application treatments, the effect of lime on decreasing the amount of N extracted from the soil and the amount recovered in the leachate can be explained by the increased quantity of N taken up in the vegetation due to enhanced growth (Table 2).

**Calcium**

Factorial analysis indicated that limestone treatment increased extractable soil Ca concentrations down to the 28-cm depth (Fig. 6). Ritchey and Schumann (2005) found an increase of 0.34 cmol kg$^{-1}$ Ca at 22.5- to 30-cm depth 3 yr after surface application of Ca(OH)$_2$ to a forest soil.

Urine decreased the concentration of Ca in the layers between 10 and 28 cm in both the limed and unlimed treatments. Peaks of NH$_4^+$ passing through the columns may have displaced Ca that then leached out along with NO$_3^−$ anions.

**Magnesium**

Factorial analysis indicated that surface application of limestone increased the concentrations of extractable Mg in all 10 layers (Fig. 7).

In the limed treatments, high concentrations of urine tended to decrease concentrations of extractable Mg between 10- and 22-cm depth, but in the unlimed treatments there was little effect of urine on extractable Mg. The source of the Mg observed in leachate from the high-urine treatments was probably Mg from the limestone rather than Mg from the soil complex.

**pH**

In soils in humid climates, it is customary to measure pH in a 0.01 mol L$^{-1}$ CaCl$_2$ solution (Schofield and Taylor, 1955) to avoid unreliably high pH measurement values that can appear at very low EC levels, such as were found in the subsoils of the low-input management system we studied (0.03 dS m$^{-2}$).

In the treatment receiving no urine and no limestone, pH$_3$ was near 4.0 throughout the profile (Fig. 8). Surface addition of limestone 46 wk before sampling to the zero-urine treat-
Aluminum

The level of extractable Al in the unlimed soil that did not receive urine was 1.4 cmol_2 kg^-1 in the surface layer and approximately 1.9 cmol_2 kg^-1 from 1.6 to 16 cm, gradually increasing to 2.8 cmol_2 kg^-1 at the bottom of the profile (Fig. 9). Below 7 cm, Al saturation was >60% for all treatments (data not shown), which is high enough to interfere with root growth of many forage and crop plants.

In the urine-free treatment, the surface addition of limestone significantly decreased KCl-extractable Al down through the top 10 cm of the profile. The overall effect of lime evaluated across all treatments was to decrease Al concentrations in the top 34 cm of the profile. The decreased concentrations of Al and higher pH_2, Ca, and Mg levels resulting from liming may explain the tendency for higher yields in the treatments receiving one and two urine applications.

Factorial analysis showed that the overall effect of urine was to decrease pH_2 in the layers between 10 and 40 cm. This was probably not due to a salt effect because the approximately 2 dS m^-1 EC of the 0.01 mol L^-1 CaCl_2 solution would have raised EC concentrations to the point where any small EC increases due to the urine treatments (0.25 dS m^-2) would not have had an effect on measured pH_2. The decreases in pH_2 may have been associated with the acidifying effects of nitrification, the presence of hippuric and uric acid in urine, or the removal of basic cations from the exchange complex by leaching.

Potassium

The control treatment showed a K concentration of 0.70 cmol_2 kg^-1 in the surface 1.6 cm of soil and 0.14 in the 1.6- to 4-cm layer, falling to around 0.07 in lower layers (data not shown). Although the one-application treatment received 10 g m^-2 K, soil concentrations tended to be lower than those in the control, probably due to the mean K uptake by the plants of 15 g m^-2 (data not shown). The two-urine application treatment received 39 g m^-2 K and the three-urine application received 71 g m^-2 K, which supplied more K than was taken up by plants. The overall effect of urine addition was to increase concentrations of K in all the layers below 2 cm, mostly due to higher concentrations in the three-application treatment and the unlimed two-application treatment. There was no clear overall effect of lime on K concentration.

Fate of Added Nitrogen

Nitrogen added to soils in the form of goat urine is subject to several transformations, and as a consequence appears in various pools. The amounts of N in four of these pools were measured, specifically: (i) N in ammonia gas released to the atmosphere, (ii) N taken up into aboveground plant material, (iii) as N recovered as extractable NH_4^+ and NO_3^- in soil, and (iv) as N present in drainage water as leached NH_4^+ and NO_3^-. The amounts of N in four of these pools were measured, specifically: (i) N in ammonia gas released to the atmosphere, (ii) N taken up into aboveground plant material, (iii) as N recovered as extractable NH_4^+ and NO_3^- in soil, and (iv) as N present in drainage water as leached NH_4^+ and NO_3^-.

Net plant uptake (above uptake in the zero-urine treatment) of N was 30 to 45% of the amount added in the one- and two-application treatments. Plant growth was seriously affected by the three-application treatments, and plant N uptake was only 9% of the N added.

In the two-application treatment, the effect of lime application in increasing plant uptake of N was statistically significant, and in the one-application treatment there was a tendency for increased uptake. This lime-induced increase in N uptake by vege-
tation presumably decreased the amounts of inorganic N available in the columns and made it difficult to evaluate the expected positive effects of liming on nitrification. Clough et al. (2004) found higher rates of nitrification and higher residual values of NO$_3^-$ at higher pH. In contrast, we found a tendency for less residual NO$_3^-$ in the limed two-application and three-application treatments. For the two-application treatment, this decrease can be explained by the increased uptake of N in plant material. In the three-application treatment, however, higher plant uptake does not explain the tendency for the limed treatment to have lower concentrations of NH$_4^+$ and NO$_3^-$ in the soil and leachate because the combination of high N rates and rate exacerbated scorching, which decreased plant growth and decreased N uptake.

The total amount of N in the leachate when the experiment ended was 14% of the N added in the one-application treatment, 15 and 7% of the amount added in the unlimed and limed two-application treatments, respectively, and >30% of the added amount in the three-application treatment. It is apparent (Fig. 2, 3, 4, and 5) that even more N would have leached in the two- and three-application treatments if the experiment had been continued longer.

During the experiment, treatments receiving zero, one, two, or three applications of urine leached a mean total of 0.1, 5, 11, and 66 g m$^{-2}$ of inorganic N, respectively. Thus, although the three-application treatment received only five times more N than the one-application treatment, it leached more that 12 times more N below 45 cm. This implies that in situations where plant growth is damaged by weight grazing, or, in our case, scorching, leaching losses of N are exacerbated by a double effect of overstocking: (i) lack of vegetation severely restricts plant uptake of N, and (ii) the absence of plants means that transpiration of rain water is reduced, thus increasing the amount of precipitation draining through the profile and increasing the rate of N leaching.

In summary, the consequences of urine additions to an acidic, dystrophic, abandoned grassland were dependent on the rate of application. With the first application of 360 kg ha$^{-1}$ of N, an increase of 53 kg ha$^{-1}$ of inorganic N was detected in soil and leachate. Where we applied larger amounts of urine to simulate a heavy stocking density of goats for land-clearing purposes, columns receiving two urine applications (975 kg ha$^{-1}$ of N) showed greater growth and greater plant uptake of N, but also greater accumulations of soil and leachate N (five times more than with a single application), mostly in the form of NO$_3^-$.

In treatments receiving three applications (1770 kg ha$^{-1}$ of N), a large amount of NH$_3$ gas was generated and the vegetation suffered scorching damage. Plant transpiration was reduced, leachate volume increased, and there were high concentrations of NO$_3^-$ and NH$_4^+$ in the soil and leachate.

Surface application of limestone 18 wk before urine application tended to increase dry matter production except in the high urine treatment, where it increased scorching damage. Limestone addition raised soil pH, increased concentrations of Ca and Mg, and decreased concentrations of extractable Al to as deep as 28 cm.

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REFERENCES


