Fertilizer Nutrient Leaching and Nutrient Mobility: A Simple Laboratory Exercise

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ABSTRACT

The ease with which fertilizers are leached through soils is a growing interest of society, and one with which students should become knowledgeable. This exercise was developed to demonstrate the degree to which N, P, and K fertilizers move through soils of different adsorption and permeability characteristics and under different leaching intensities. Rainfall equivalent to 13 cm did not leach fertilizers through a 60-cm column of dry sandy loam soil. Addition of 54 cm water resulted in leaching 57% of the applied N, 0% P, and 42% of the K. In a related exercise, students are led through a series of calculations to estimate relative mobility of N, P, and K in soil based on routine chemical analysis of column leachate and a surface layer of soil after leaching is completed. On a scale of 1 to 10 (10 = most mobile), mobility was 9.9 for N, 0.1 for P, and 3.3 for K. The results support the common practices of broadcasting N, but banding P and K for maximum efficiency.

SOCIETY'S GROWING CONCERN of the effects of farming practices on groundwater quality creates an interest in leaching of agricultural chemicals from soil. The importance of movement of fertilizer nutrients with respect to soil type and rainfall environment must be stressed to students planning to work in the agronomic crops area. With this in mind, an exercise was designed to demonstrate leaching and relative mobility in soil of different fertilizer nutrients.

Although dyes have commonly been used to demonstrate movement of materials through soils, the leaching of fertilizer nutrients in laboratory exercises has not been reported. Bowman et al. (1988) used a 0.01 *M* $CaCl_2$ saturated sand column and dyes to demonstrate miscible displacement and the rapid leaching of CrO_4^{2-}, which they suggested was similar to movement of NO_3^-. Williams (1985) used anionic (methyl orange) and cationic (methylene blue and basic fuchsin) dyes to demonstrate the effect of soil cation exchange capacity on movement of cations and anions through a sandy soil. Similarly, Butters and Bandaranayake (1993) used cationic and anionic dyes to demonstrate solute transport through soil columns.

This exercise consists of placing two soils with differing permeability and nutrient retention capacities into several transparent tubes. Fertilizer compounds are added and columns leached with different amounts of water to represent high rainfall and low rainfall environments. The high rainfall amount is enough to readily leach mobile nutrients through the column of soil while the low rainfall amount is enough to move the wetting front to the end of the tube without solution leaving the tube. Water passing through the soil (leachate) is collected in increments that represent fractions of a total pore volume for the soil used. Leachate samples are analyzed. For Part II of the exercise a surface layer of soil is removed for nutrient analysis. This exercise was used in an undergraduate soil fertility course at Oklahoma State University.

Objectives for development of the teaching-learning exercise in nutrient mobility were: (i) develop a technique to demonstrate fertilizer nutrient movement in the soil, (ii) devise a system of calculations to interpret data obtained from the exercise, and (iii) determine relative nutrient mobility.

MATERIALS AND METHODS

Part I. Fertilizer Nutrient Leaching

Soil Column Preparation

Approximate pore volumes for loam and sandy loam soils are determined by weighing a 100-mL graduated cylinder, and then adding dry soil while gently tapping the cylinder on the lab bench top until the cylinder is filled. The cylinder plus soil is then weighed and soil weight calculated. Bulk density (BD) is calculated by dividing the weight of the soil (g) by the volume (100 cm^3). Assuming a particle density (PD) of 2.65 g cm^{-3}, the percentage of soil volume occupied by solids is then given by (BD/PD)100 = % solids. The percent porosity is determined by subtracting the percent solids from 100. The soil columns are created by filling capped transparent plastic tubes (100 cm long by 4.34 cm i.d.; part no. BL 1750; Giddings Machine Co., Ft. Collins, CO) to a depth of 60 cm from the bottom with dry soil. When filling the tubes with loam or sandy loam soils, the students should lightly tap the columns to try to approximate the packing of soil in the 100-mL graduated cylinder when bulk density was determined. A filter paper disc slightly smaller than the tube diameter is placed on the soil surface to reduce soil mixing when solution is added to the columns. The tubes are placed on a display rack and labeled to identify the following fertilizer leaching conditions: L/LR/C, L/LR/F, L/HR/C, L/HR/F, S/LR/C, S/LR/F, S/HR/C, S/HR/F, where L = loam, S = sandy loam, LR = low rainfall, HR = high rainfall, C = control, and F = fertilized. The pore volume of each column will equal the volume of soil column ($V = \pi r^2 L$) times the porosity.

Fertilizer Preparation and Addition

The solution containing fertilizer nutrients is prepared to approximate a 224 kg ha^{-1} (200 lb $acre^{-1}$) fertilizer addition of each nutrient. To 400 mL of distilled water (enough for 10 replications), 618 mg of $(NH_4)_2HPO_4$, 573 mg of

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Abbreviations: ICAP, induction coupled argon plasma.

NH_4NO_3, and 528 mg of KCl were added,. For nitrogen (N), phosphorous (as P_2O_5), and potassium, (as K_2O) a total of 33.2 mg of each will be contained in a 40-mL volume. In terms of the elemental concentration the 40 mL additions represent 23.1 mg NH_4–N, 10 mg NO_3–N, 14.5 mg P, and 27.8 mg K. Students add the fertilizer solution to each of the fertilized columns of soil and 40 mL of distilled water to the control columns then observe the downward movement of the wetting front. After the wetting front appears to have stopped (48 h), the front is marked by making a line on the tube. The distance from the soil surface is measured and recorded. Inverted beakers placed over the column tops minimizes evaporative loss of solutions. Development of the exercise to this point may be accomplished in a 2-h lab period.

Leaching the Columns

Distilled water is added to soil columns to simulate rainfall. An amount equal to one-half a pore volume is added to each of the low rainfall treatments. Funnels and leachate collection containers (marked to indicate one-fourth leaching volumes) are placed under the high rainfall treatment soil columns. Water is periodically added to maintain a "head" on the top of these columns until a total of two pore volumes have been applied. Students observe the collection of leachate in the containers below the soil columns. After each one-fourth pore volume leaches through, another empty container (calibrated) is placed under the column and the collected leachate is poured into a graduated cylinder, the volume recorded, and a portion transferred to an analysis sample container and labeled. Anticipate rapid leaching in the sandy loam soil and much slower leaching in the loam soil. A collection of four or five one-fourth pore volumes will be sufficient. Technically there is enough water for eight one-fourth pore volumes but, about one-half pore volume will remain in the columns at field capacity. Because the loam soil will leach much slower, someone will have to monitor the columns throughout the day until enough one-fourth pore volumes leach through. It is not highly critical that the collected samples measure exactly one-fourth pore volume but they should not vary greatly. When all the samples are obtained and labeled appropriately, they are sent to the laboratory for analysis. The laboratory used automated flow injection analysis (Lachat, 1989, 1990) for NH_4^+– and NO_3^-–N, colorimetric (phosphomolybdenum blue) analysis of P and atomic emission spectrophotometric analysis (ICAP) of K for solutions. Soil was extracted using a saturated $CaSO_4$ solution for NO_3^-–N, and Mehlich-3 (Mehlich, 1984) for P and K. However, these extraction and analytical methods are not unique to the success of this exercise. Any reliable analytical method, and any extraction method that is capable of extracting the chemical form of the nutrient added, will be acceptable.

Interpreting the Data

When the laboratory analysis is completed, laboratory data sheets (reporting nutrient concentrations in ppm) together with several tables and graph paper are made available to the students. The students must follow stepwise calculations through the series of tables to determine how much of each fertilizer material leached through the soils. Actual data, collected for a sandy loam soil, shown in Table 1 are labeled to record leachate analysis from fertilized and control treatments. The ppm concentrations reported by the testing laboratory are equivalent to, and entered in Table 1 as mg L^{-1}. The nutrient concentrations reported in Table 1 are converted to total amount of nutrient, expressed as mg, in each leachate in Table 2. This conversion is made by multiplying the volume of each leachate (L) times the concentration (mg L^{-1}) for each nutrient. Leachate volumes and % pore volumes should be similar for the fertilized and control columns.

To account for the amount of nutrient already present in the soils, the data for the control columns is subtracted from data for the fertilized columns, and the differences identified as fertilizer nutrient leached in the spaces designated L in Table 2. This defines the amount of nutrient in each leachate and the total amount of nutrient leached when the data is added. Table 3 provides a place to record the amount of each nutrient leached as a percent of the total added. Students can then prepare a graph from the data in Table 3 of "percent of added nutrient leached" vs. "pore volumes of solution

Table 1. Concentration of nutrients leached through fertilized (F) and control (C) soil.

Leachate		Pore	NH_4^+-N		NO_3^--N		P		K	
Number	Volume	volume	F	C	F	C	F	C	F	C
	L	%	mg L^{-1}							
1	0.114	28.5	1.8	1	78.6	69	1	1	44	31
2	0.106	26.5	4.0	1	69.4	8	1	2	43	14
3	0.100	25.0	4.9	1	19.9	8	2	2	36	12
4	0.100	25.0	4.7	1	2.6	1	3	2	24	8
5	0.122	30.5	3.2	1	1.7	1	4	2	18	7
6	0.066	16.5	2.9	1	1.9	1	5	2	16	7
Total	0.523	130.8								

Table 2. Amount of nutrient leached (L) as a difference of fertilized (F) and control (C).

Leachate	NH_4^+-N			NO_3^--N			P			K		
number	F	C	L	F	C	L	F	C	L	F	C	L
	mg											
1	0.2	0.1	0.1	9.0	6.9	3.1	0.1	0.9	–0.8	5.0	2.9	2.1
2	0.4	0.1	0.3	7.4	0.8	6.6	0.1	0.2	–0.1	4.6	1.4	3.2
3	0.5	0.1	0.4	2.0	0.8	1.2	0.2	0.2	0.0	3.6	1.0	2.6
4	0.5	0.1	0.4	0.3	0.1	0.2	0.3	0.2	0.1	2.4	0.7	1.7
5	0.4	0.1	0.3	0.2	0.1	0.1	0.4	0.2	0.2	2.2	0.7	1.5
6	0.2	0.1	0.1	0.1	0.1	0.0	0.3	0.1	0.2	1.1	0.4	0.7
Total	2.2	0.6	1.6	19.0	8.8	10.2	1.2	1.8	-0.6	18.9	7.1	11.8

Table 3. Solution and fertilizer nutrients† leached as a percentage of total added.

Leachate number	Solution‡	NH_4^+-N	NO_3^--N	P	K
	cumulative totals	%			
1	0.29	0.4	31	–5.5	7.6
2	0.55	0.5	66	–0.7	11.5
3	0.80	0.4	12	0.0	9.3
4	1.05	0.4	2	0.7	6.1
5	1.36	0.4	1	1.4	5.4
6	1.52	0.5	0	0.0	2.5
Total	1.52	2.6	112	–4.1	42.4

† Amounts (mg) added were: NH_4^+-N = 23.1; NO_3^--N = 10.0; P = 14.5; K = 27.8.
‡ Total pore volumes of solution collected, cumulative totals.

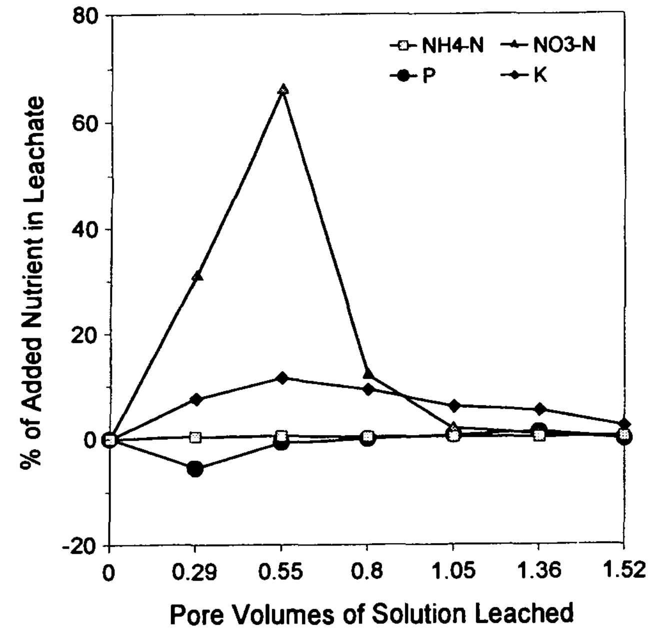

Fig. 1. Movement of fertilizer nutrients through intensively leached sandy loam soil.

leached" to visualize how rapidly the different nutrients leached through the soil (Fig. 1).

Part II. Relative Mobility of Nutrients

Sectioning the Soil Columns

The second part of the exercise deals with analysis of soil in the columns from Part I after the leaching process is finished. The columns are marked at 7.5 cm from the top of the soil surface and soil removed to that depth and placed into individually labeled soil testing sample containers that are collected by the instructor to send to the lab for analysis.

Data from the laboratory analysis, when complete, is once again given to the students, along with another set of prepared tables. The amount of each nutrient extracted from the soil column segment is recorded in Table 4. Nutrient concentrations (mg kg^{-1}) are converted to mg as in Part I (bulk density is multiplied times soil volume removed to estimate total dry soil [kg] extracted). Data for the control columns is again subtracted from data for fertilized columns and differences entered as amount of fertilizer nutrients remaining (Table 5). The amount of nutrient remaining as a percent of total added is also calculated and recorded in Table 5. Relative mobility based on leachate analysis and relative immobility based on soil analysis of the nutrients are then calculated and recorded in Table 6. This is accomplished by dividing the highest percentage of added nutrient found into all of the others (after adjusting for negative values) and multiplying by 100. Mobility and immobility are assumed to total 100, hence percent immobility can be transformed to mobility to allow comparison of mobility values estimated by two different approaches. Mean relative mobility is the average of the two mobility values in each half of Table 6.

Table 4. Nutrients extracted from surface layer of fertilized (F) and control (C) soil columns.

NO_3^--N		P		K	
F	C	F	C	F	C
mg kg^{-1}					
2.0	6.0	85	42	103	49
mg†					
0.3	1.0	13.7	6.8	16.6	7.9

† Calculated by multiplying mg kg^{-1} concentration times kg dry soil in 7.5 cm surface layer.

Table 5. Fertilizer nutrients retained in surface of intensively leached soil.

NO_3^--N	P	K
mg†		
−0.7	6.9	8.7
% of added‡		
−7	48	31

† Obtained by subtracting F − C for mg in Table 4.
‡ Obtained by dividing mg retained by total mg added and multiplying by 100.

Table 6. Relative mobility and immobility of fertilizer nutrients.

Data group	NO_3^--N	P	K
	%		
Mobility			
Nutrient in leachate	112	−4	42
Relative mobility†	100	1	40
Immobility			
Nutrient retained in soil	−7	48	31
Relative immobility‡	2	100	71
Relative mobility§	98	0	29
Mean relative mobility	99	1	33

† Positive values obtained by adding 5 to each % nutrient in leachate value, dividing each by the largest value (117) and multiplying by 100.
‡ Positive values obtained by adding 8 to each % nutrient in soil value, dividing each by the largest value (56) and multiplying by 100.
§ Obtained by subtracting relative immobility from 100.

DISCUSSION

The demonstration along with the laboratory results are used to simulate the movement of fertilizer nutrients added to the soil. It is important for students to understand the high rainfall treatment is a "worst case" scenario that does not allow for evapotransporation or runoff. Furthermore, absence of a crop and the short period for leaching, minimize nutrient removals by crop uptake and immobilization that would reduce leaching potential, especially for N. The behavior of these fertilizer materials is clearly illustrated. In Part I, students observe the relative ease of movement of the nitrate (NO_3^-) in comparison to ammonium and the other fertilizer nutrients. The exercise also demonstrates the effects of rainfall on fertilizers applied to the soil. The low rainfall treatments (one-half pore volume) that do not produce any leachate, contrast with the high rainfall treatments. Thus areas with high rainfall or excessive use of irrigation water can result in removal of NO_3^- from the root zone. The effect of soil type on rate of leaching is indicated by how rapid leachate moves through the sandy loam in comparison to the loam soil in Part I, and the location of highest concentration from Part II (data not shown). Also the amount of rainfall necessary to significantly leach fertilizer nutrients can be implied. For example, with the columns described, the 40 mL of solution used to add the fertilizer chemicals was equivalent to about 2.54 cm of rainfall, which resulted in a 15 to 20 cm wetting front. The low rainfall treatment was equivalent to 13.5 cm and the high rainfall 54.1 cm of water. From the comparison of these two treatments students realize considerable rainfall (without runoff or evapotranspiration) is necessary to leach nutrients through 60 cm of soil. Furthermore, as illustrated in Fig. 1, some fertilizer materials are not easily leached even under high rainfall conditions. Part II provides the students with a useful reference as to where in the soil profile the nutrients are likely to accumulate in relation to each other. Although it was not our objective, the soil column could be partitioned into several layers, each extracted and analyzed separately if complete recovery of added nutrients is of interest. Chemical and biological changes makes this difficult, however. Even in the short period used, there was apparent nitrification of ammonium resulting in the amount of NO_3^- leached exceeding 100%. As prepared, the soil columns represent a tilled soil without macropores that maximizes soil-solute interaction as solution moves through the columns.

Student interest in the exercise was high. In the course taught at Oklahoma State University, the exercise was completed within 3 wks and students submitted separate reports for Parts I and II. This exercise differs from other demonstrations that use colorful dyes to illustrate chemical transport because actual fertilizer materials and rates on a particular soil are used. This exercise would also be useful in courses that address water quality.

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