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Effects of land use on leaching of nitrate-N, ammonium-N and phosphate in relation to stained surface area**

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A b s t r a c t. The chemical leaching is largely related to the land use and associated management practices. The aim of this study was to examine leaching of NO_3-N, NH_4-N and PO_4-P from tilled and orchard silty loam soil in column experiments. The experimental objects included: a conventionally tilled field with main tillage operations including pre-plow (0.1 m) + harrowing, mouldboard ploughing (0.2 m), and a 35 year-old apple orchard with a permanent sward. Concentrations in the leachate and total leaching of NO_3-N were greater and those of NH_4-N were lower in the CT than in the OR soil. Irrespective of the management system total percentage of the NO_3-N collected in the leachate correspond to 15.5-17.2% of applied NO_3-N and was substantially greater than that of NH_4-N (0.47-0.85%). Leaching of the indigenous PO_4-P was appreciably greater from the tilled soil than from the orchard soil. The stained surface area at the 2-8 cm horizontal sections was greater under tilled soil than orchard soil, and lower at 10-18 cm depths. The results indicate the potential of management practices in the control of leaching of the macroelements.

K e y w o r d s: tilled soil, orchard soil, soil structure, leaching, macroelements

INTRODUCTION

Studies on land use and soil management effects are important due to environmental and economic impacts. The nutrient concentration in the soil solution and leaching can be significantly affected by the type of land use and associated degree of soil disturbance, fertilization and rainfall intensity (Ulén and Johansson, 2009; Woli *et al*., 2002).

Intense leaching can increase nitrate concentration in drainage water above the level of 10 mg NO_3-N l^{-1} being considered the safe limit for drinking water (Booltink, 1995). Moreover, the nitrogen leached to the deeper soil may remain available for losses by N_2O emission to the atmosphere as a result of denitrification (Mkhabela *et al*., 2008; Sawamoto *et al*., 2003).

Research has shown that less intense tillage compared with conventionally tilled soil, results in significant changes of soil physical properties (Czyż and Dexter, 2009) and reductions in nitrate concentration in drainage water and total N losses and can be more advantageous from the point of view of N conservation, recycling and quality of the ground water (Lipiec and Stępniewski, 1995; Stout *et al*., 2000) although downward transport of nitrogen in non-tilled soil can be faster. Hansen and Djurhuus (1997) reported that nitrate leaching was greater from autumn than spring ploughed plots and on loamy rather than sandy soil. Studies revealed that no-till compared to tilled soil stimulated more losses of NH_4-N than of NO_3-N.

Phosphate leaching losses are relatively small (<1 kg ha^{-1} $year^{-1}$) but they can be environmentally significant when combined with the surface run-off losses (Puustinen *et al*., 2005) and may exceed critical concentration levels for eutrophication (0.08-0.12 mg P l^{-1}). Phosphate losses by leaching are influenced by management system and soil P concentration (McDowell and Sharpley, 2004).

Chemical leaching under different management system depends on contributions of pores of various size influencing both transmission and retention and sorption soil functions. The role of large pores (macropores) in rapid infiltration was stressed in several papers (Gerke, 2006; Pagliai *et al*., 2004; Shein *et al*., 2010; Siczek *et al*., 2008). Macropores can serve as preferential flow paths of water and

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chemicals into deeper layers of the soil profile and the groundwater zone, bypassing the bulk of the soil matrix (Booltink, 1995). This flow often occurs in no-till or grassed soil with worm-formed pores that are open to the surface and continuous with depth. Grass covered soil is a common practice in orchards (Lipecki and Berbeć, 1997) and vineyards. Preferential flow may also occur in ploughed soil (Levanon *et al*., 1993) with a stable structure preserving the pore network and associated low susceptibility to sealing along interaggregate pores (Kutílek, 2004; Lipiec *et al*., 2006). The proportions of pores of various sizes are interrelated. In general decrease in the proportion of large transmission pores is accompanied by greater the proportion of small storage pores.

The chemical leaching is also related to the soil organic matter (SOM) and nature of the given chemical. The increased SOM content can reduce leaching of the reactive chemicals, *eg* ammonium N, phosphate due to sorption, and on the other hand, it can enhance earthworm activity and hence the development of burrows that may support preferential flow and thereby leaching (Addiscott and Thomas, 2000). This leaching can be further reduced by organic linings and by the presence of Fe and Al oxides in the burrow wall material that may adsorb chemicals as well as allow the growth of microorganisms which transform chemicals into less chemically active forms. It was observed less leaching of the strongly reactive phosphate from biological pores compared to interaggregate pores or fractures. Although a number of studies have improved our knowledge on nutrient leaching as related to type of soil management system there is still a need to get further understanding of nitrogen and phosphorus leaching by conducting experiments under controlled conditions taking into account pore structure and SOM that are influenced by soil management practices (Carter, 2004).

The aim of this study was to examine the leaching of nitrate-N, ammonium-N and phosphate from tilled and orchard silty loam soil related to soil structure – stained surface area.

MATERIAL AND METHODS

The experiment was accomplished on an Orthic Luvisol derived from loess, over limestone, at the experimental field of the Lublin University of Life Sciences in Felin, Poland (51°15'N, 22° 35'E), 210 m a.s.l. Annual mean temperature and precipitations at the site are 7.4°C and 572 mm, respectively.

The management systems were: (CT) conventionally tilled field (100x150 m) with main tillage operations including pre-plow (0.1 m) + harrowing, mouldboard ploughing (0.2 m) and crop rotation including selected cereals, root crops and papilionaceous crops, (OR) 35 year-old apple orchard field (100x200 m) with a permanent sward that was mowed in the inter-rows during growing season. The current management practice on CT was applied over approximately last 30 years. Both fields were situated in the area with a uniform soil texture. The above management systems were selected to have different pore structure on the same type of soil. Total porosity was calculated based on dry bulk density and the particle density of the soil (2.62 Mg m^{-3}). For determination of dry bulk density on an oven-dry basis (Klute, 1986), core samples of 100 cm^3 volume and 0.05 m diameter were collected from the field in 4 replications. The soil organic matter content was determined by wet oxidation using the Tiurin method. Content of NO_3-N, NH_4-N and PO_4-P in the soil was determined in extracts (0.01 M $CaCl_2$) using flow-type spectrophotometric analyzer, FIA-Star 5010 (Foss Tecator) and pH – by glass electrode method. The OR soil compared to the CT is characterized by higher total porosity, content of NH_4-N, soil organic carbon and pH and lower contents of NO_3-N and PO_4-P (Table 1).

Leaching of the chemicals was determined in soil columns, taken with steel cylinders of 0.215 m inner diameter and 0.2 m depth of 0-0.2 m (3 replicates) in autumn, for CT – after harvest of spring wheat. To minimize soil damage, the cylinders were slowly pressed into the soil with a hydraulic jack. The column size was large enough to be the representative elementary volume of soil with undisturbed structure for measurements of water and solute movement.

In the laboratory the soils were pre-wetted with water in order to obtain the field water capacity at which mean water contents were 0.203 and 0.226 kg kg^{-1} in CT and OR soils, respectively. Then 0.5 g of granular NH_4 NO_3 (equivalent to a rate of 47 kg N ha^{-1}) was placed uniformly onto the surface of each core. We used NH_4 NO_3 that is a significant source of N used in Poland. The cylinders were then subjected to watering at an amount of 30 mm (1 100 ml) of distilled water. On average rainfalls of such size occur in the experimental area 4 times a year. Water was applied using a manual irrigation system in 100 ml doses to keep shallow ponding (a few mm) during infiltration. Each successive 100 ml dose started when 1 mm of ponding water remained after the previous one. To avoid soil structure damage by water we used a filter paper on the soil surface at irrigating.

Infiltration rates for each cylinder were recorded as soon as the columns began to produce leachate. All the leachate was collected in 50 ml increments from each column separately to analyze the concentration of NO_3-N, NH_4-N, PO_4-P using flow-type spectrophotometric analyser, Foss Tecator FIA-Star 5010. The results obtained were then plotted in the form of curves in which the concentration of the nutrients (mg l^{-1}) was presented as a function of consecutive 50 ml leachate increments.

To analyze the stained surface area 30 mm of brilliant blue solution (4 kg m^{-3}) were infiltrated into the same columns that were used to determine nutrient leaching. A few mm head of the solution was maintained during the infiltration. Then the columns were sectioned horizontally at 0.02 m depth intervals. Photographs of each section were used to estimate brilliant blue stained surface area (SSA) for

T a b l e 1. Some physical and chemical characteristics of the tilled and orchard soils

Depth (m)	Particle size (mm) distribution			Total porosity	C_{org}	pH_{H_2O}	NO_3-N	NH_4-N	PO_4-P
	2-0.02	0.02-0.002	<0.002						
			(%)					(mg kg^{-1})	
				Tilled soil (CT)					
0-0.1	66	28	6	47.30	1.17	5.91	69.70	12.80	1.91
0.1-0.2	62	29	9	38.20	1.13	5.80	52.40	11.50	2.12
				Orchard soil (OR)					
0-0.1	71	27	2	49.20	1.77	6.36	52.90	14.30	0.76
0.1-0.2	70	23	7	48.90	1.59	6.40	38.30	14.10	0.66

pores greater than 117 μm and to calculate number of macropores of equivalent diameter larger than 2 mm using a colour digital camera (Canon EOS 300D) and the program Scion Image for Windows (Scion Corporation).

RESULTS AND DISCUSSION

The course of NO_3-N concentration as a function of the leachate volume was different in the treatments (Fig. 1a). Under CT the concentration initially sharply decreased and then gradually increased in consecutive leachate samples whereas under OR it did not change substantially in all the leachate. In most 50 ml leachates the nitrate concentrations were less from beneath the OR than the CT columns. In particular, the differences were pronounced in the two first 50 ml leachates and then after 350 ml of water had been passed. The differences can be attributable to flushing the matrix CT soil having a higher indigenous nitrate-nitrogen concentration than the OR soil (Table 1). Moreover, a greater concentration of organic carbon (C_{org}) content and lower nitrate concentration in OR than CT implies a greater C/N ratio in the OR that can result in lower NO_3-N leaching due to N immobilization.

The cumulative percentage of NO_3-N applied in leachate shows that the leaching of NO_3-N was approximately linear throughout the leaching event in both treatments (Fig. 1b). The linearity corresponds with a relatively stable NO_3-N concentration in leachates after 100 ml of water had been passed (Fig. 1a). Total percentage of the NO_3-N applied recovered in the leachate was 17.2% for CT and 15.5% for the OR soil although the amount of leachate produced was somewhat greater from the OR columns. This indicates higher efficiency in nitrate leaching of CT than OR leachate solution.

The concentration of NH_4-N under CT decreased with increasing leachate volume mostly in the first 7 leachates and then remained at almost the same level (Fig. 2a) whereas slightly decreased over leachates under the OR. In a majority of leachates the concentration of NH_4-N was greater

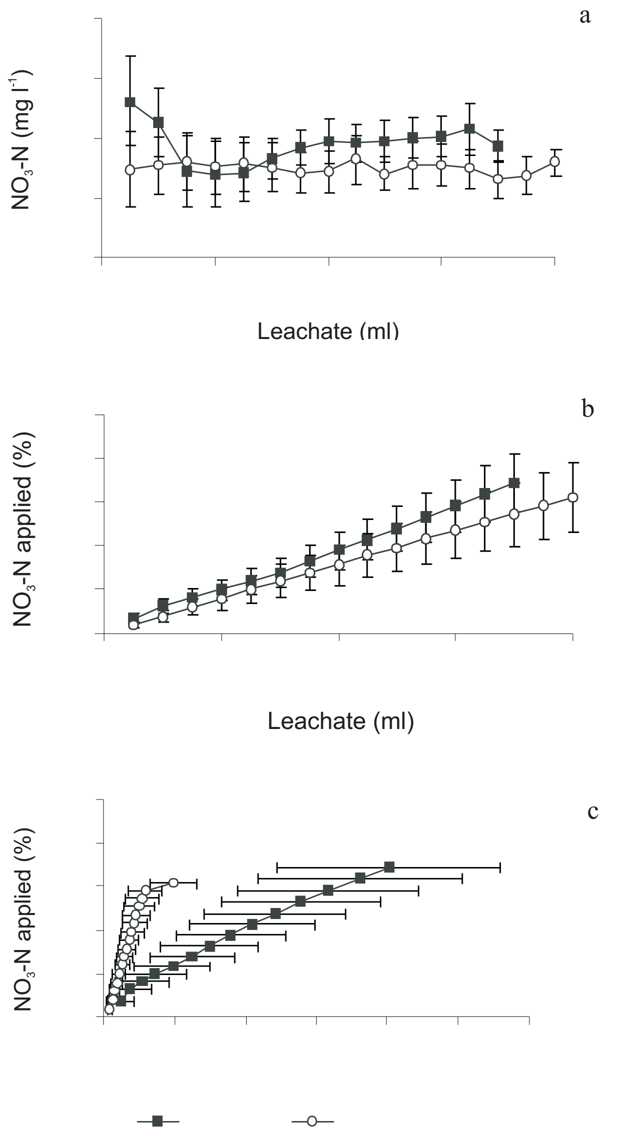

Fig. 1. Concentration of NO_3-N in leachate (a), cumulative % of NO_3-N applied in leachate (b) and cumulative % of NO_3-N applied as a function of time (c). The bars represent standard deviations.

under OR than CT and as a consequence cumulative percentage of the NH_4-N applied recovered in leachate was 0.47% for CT and 0.85% for the OR soil (Fig. 2b).

Concentrations of PO_4-P were higher in the leachate solution from the CT (2.34-2.98 mg l^{-1}) than the OR (0.09-0.05 mg l^{-1}) columns with the largest differences at the end of leaching event due to increasing phosphate concentration in consecutive 50 ml leachates from the CT columns (Fig. 3a). The lower phosphate concentration in the leachate from OR than CT columns can be due to three times lower mean PO_4-P content at 0-0.2 m depth (0.71 *vs.* 2.01 mg kg^{-1}) and lower acidity (Table 1). The concentrations were reflected in cumulative quantity of PO_4-P that appreciably increased with increasing volume of leachate under CT whereas under OR it was lower and remained almost steady throughout the leaching event (Fig. 3b).

Figures 1c, 2c and 3c indicate that leaching of the macroelements occurred earlier from the OR than CT soil that can be related to different stained surface area and associated infiltrability. Greater stained areas in the upper part and lower in the deeper part of the CT than OR columns also can be indicative of greater matrix flow under the CT (Fig. 4). In both management systems the stained surface area as a function of depth could be described by logarithmic equation: $\ln(x) = a + b\,y$, where – x is the surface stained area (% of total area), a and b are fitted coefficients, and y is the depth (m). The higher (less negative) values for the coefficient b in the equations for OR than CT soil imply more continuous and conductive pores in the former. These results support other findings indicating that the management practices with less soil tillage exhibit a greater continuity and connectivity of the macropore system (Shipitalo *et al.*, 2000).

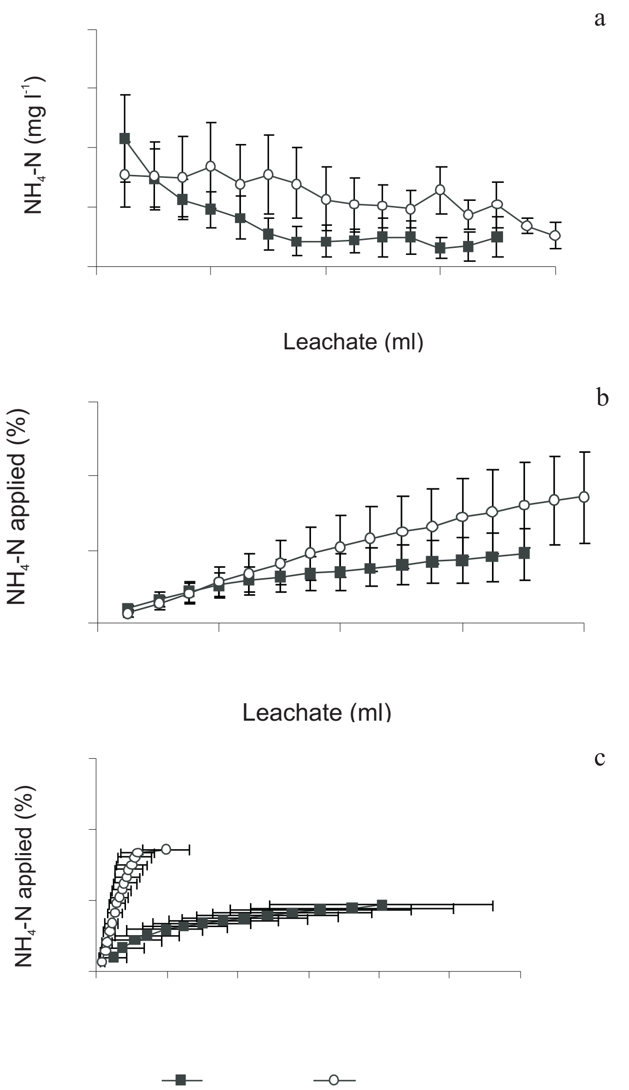

Fig. 2. Concentration of NH_4-N in leachate (a), cumulative % of NH_4-N applied in leachate (b) and cumulative % of NH_4-N applied as a function of time (c). Explanations as in Fig. 1.

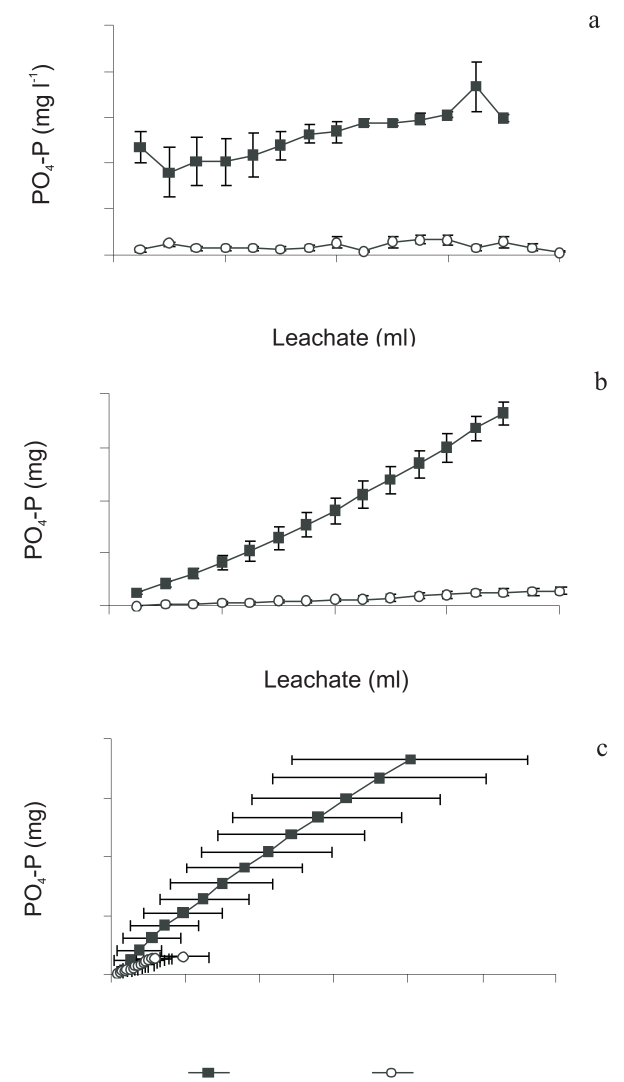

Fig. 3. Concentration of PO_4-P in leachate (a), cumulative % of PO_4-P applied in leachate (b) and cumulative amount of PO_4-P as a function of time (c). Explanations as in Fig. 1.

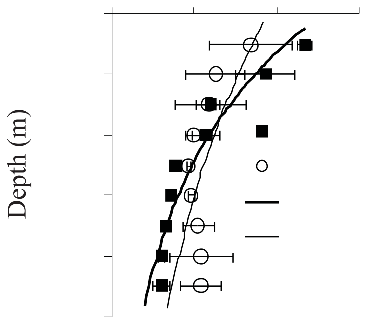

Fig. 4. Stained surface area (SSA) with depth for two management systems. Explanations as in Fig. 1.

T a b l e 2. Number of macropores (equivalent diameter > 2 mm) per horizontal section (0.036 m^2) and average area of one macropore

Pores	Tilled soil (CT)	Orchard soil (OR)
Number of pores	8.58 (1.33)	14.00 (2.67)
Pore area (mm^2)	7.32 (0.94)	10.01 (3.28)

Standard error is given in the brackets.

Table 2 presents number and area of macropores of equivalent diameter larger than 2 mm calculated as average of macropores counted on each horizontal sections (0.036 m^2). It is worthy of noting that stained areas in OR compared to CT soil were mostly concentrated around the more numerous large earthworm-formed burrows (Fig. 5). The areas can be planes of weakness that were preferentially burrowed by earthworms. High contribution of biological pores formed by earthworms in orchard soil was also observed using the resin-impregnated sections.

The differences in the rate of water flow and organic matter content between the management treatments help to explain differences in leaching rate of the macroelements. In the case of NO_3-N a greater cumulative leaching from beneath OR than CT columns for comparable time intervals (Fig. 1c) can be due mostly to higher soil infiltration rate at saturated conditions in the same management objects under field conditions. As to the reactive NH_4-N the lower cumulative leaching percentage at each comparable time elapsed from beneath the less conductive CT than OR columns (Fig. 2c) implies longer period of time available for interaction with the soil cation exchange complex that would lessen NH_4-N leaching in the CT. Under field conditions low intensive rain events and associated low infiltration rate may enhance conversion of NH_4-N to more mobile NO_3-N and thereby its leaching.

These results are in agreement with those of Shipitalo *et al*. (2000) who observed greater losses of Sr^{2+} that mimics the behaviour of NH_4-N under no-till, with a more prevalent preferential flow through the large pores, than in tilled soil. Significant role of large pores in leaching of NH_4-N was clearly shown that the amount of NH_4-N leached from a pasture soil at 0 kPa pressure was substantially greater than at 0.5 kPa pressure when large pores (> 600 μm) were emptied and did not take part in the transmission. As to phosphate the enhancing effect of greater leaching rate in OR soil was compensated for by a considerably lower phosphate concentration in all 50 ml leachates (Fig. 3a) and consequently resulted in lower leaching under OR than CT at comparable times (Fig. 3c). The results on the concentration of the macronutrients in the leachate solution provide further insight into the nature of leaching and can get better assessment of total chemical loading and thereby risk of environmental pollution depending on soil management system.

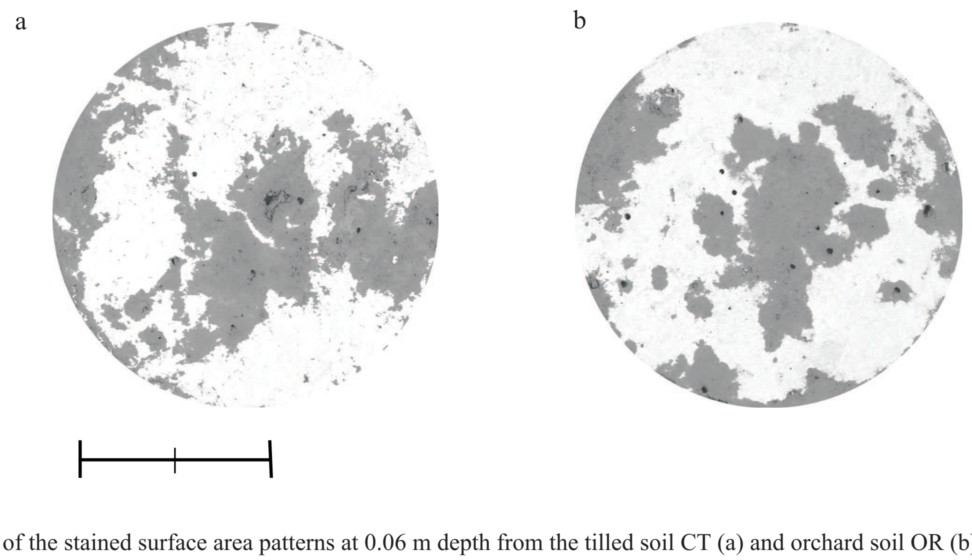

Fig. 5. Examples of the stained surface area patterns at 0.06 m depth from the tilled soil CT (a) and orchard soil OR (b).

CONCLUSIONS

1. The results of column experiment indicate that the type of soil management system had a strong influence on leaching of the macroelements by altering organic matter content, structure and flow rate and concentration of the elements in the soil.

2. The total leaching of NO_3-N and PO_4-P was greater and that of NH_4-N was lower beneath the tilled soil than the orchard soil columns however the leaching rate of all the macroelements was quicker from orchard soil.

3. Surface stained area and contribution of large pores indicate a greater matrix flow in tilled soil than orchard soil that influenced leaching in a different way depending on type and nature of the macroelements.

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