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Abstract

The impact of tillage and nitrogen (N) application method on the spatial variation on leaching losses was evaluated using eight, 1-m³ undisturbed soil monoliths. Monoliths were collected in 1992 from research plots with 15 years of continuous tillage and crop rotation history. Tillage practices imposed in the field were moldboard plow, chisel, or ridge tillage. Anion tracers were applied to simulate applying N as a surface broadcast, in a slot with surface compaction, and with water. A rainfall simulator was used to apply 100 mm of water followed 24 h later by an additional application of 430 mm to establish tracer concentrations over a range of drainage. Drainage was collected at the bottom of each monolith using fiberglass wick extractors placed in a 6 × 6 grid of 90 mm × 90 mm cells. Tracer leaching losses and flow-weighted concentrations were calculated from the initial flush of water through 24 h after water application. No significant differences were noted for cumulative drainage distribution curves or for the depth of drainage produced ($p < 0.05$). However, in all cases, the cumulative distribution curves were above the 1:1 line, indicating that drainage from some cells was greater than others. Spatial analysis indicated that drainage was randomly distributed across the monolith. Tracer leaching losses were not significantly different among tillage treatments or tracer application methods for either water application event. However, results for the slot with surface compaction treatment suggest that 10 times more NO₃-N from moldboard plow treatment in comparison with the ridge tillage treatment. Trends in leaching losses for the SLOT (Br) with surface compaction treatment suggested that a tracer leaching pattern existed directly below the application zone. Tracer concentrations peaked above 350 mg L⁻¹ after 100 to 170 mm of drainage for the SLOT (Br) with surface compaction application method and final concentrations remained above 70 mg L⁻¹. Peak concentrations for the surface broadcast (BROAD) and with water application (WATER) methods peaked at less than 110 mg L⁻¹ and were consistent among monoliths. Spatial analysis indicated that leaching losses were randomly distributed. Data supported an assertion that the moldboard plow tillage treatment combined with the slot with surface compaction (SLOT) application of N should be avoided.

Keywords

Nitrate leaching, Fiberglass wicks, Preferential flow, Monoliths

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IMPACT OF TILLAGE AND TRACER APPLICATION METHOD ON SPATIAL DISTRIBUTION OF LEACHING LOSSES

W. L. Kranz, R. S. Kanwar

ABSTRACT. *The impact of tillage and nitrogen (N) application method on the spatial variation on leaching losses was evaluated using eight, 1-m³ undisturbed soil monoliths. Monoliths were collected in 1992 from research plots with 15 years of continuous tillage and crop rotation history. Tillage practices imposed in the field were moldboard plow, chisel, or ridge tillage. Anion tracers were applied to simulate applying N as a surface broadcast, in a slot with surface compaction, and with water. A rainfall simulator was used to apply 100 mm of water followed 24 h later by an additional application of 430 mm to establish tracer concentrations over a range of drainage. Drainage was collected at the bottom of each monolith using fiberglass wick extractors placed in a 6 × 6 grid of 90 mm × 90 mm cells. Tracer leaching losses and flow-weighted concentrations were calculated from the initial flush of water through 24 h after water application. No significant differences were noted for cumulative drainage distribution curves or for the depth of drainage produced ($p < 0.05$). However, in all cases, the cumulative distribution curves were above the 1:1 line, indicating that drainage from some cells was greater than others. Spatial analysis indicated that drainage was randomly distributed across the monolith. Tracer leaching losses were not significantly different among tillage treatments or tracer application methods for either water application event. However, results for the slot with surface compaction treatment suggest that 10 times more NO₃-N from moldboard plow treatment in comparison with the ridge tillage treatment. Trends in leaching losses for the SLOT (Br) with surface compaction treatment suggested that a tracer leaching pattern existed directly below the application zone. Tracer concentrations peaked above 350 mg L⁻¹ after 100 to 170 mm of drainage for the SLOT (Br) with surface compaction application method and final concentrations remained above 70 mg L⁻¹. Peak concentrations for the surface broadcast (BROAD) and with water application (WATER) methods peaked at less than 110 mg L⁻¹ and were consistent among monoliths. Spatial analysis indicated that leaching losses were randomly distributed. Data supported an assertion that the moldboard plow tillage treatment combined with the slot with surface compaction (SLOT) application of N should be avoided.*

Keywords. *Nitrate leaching, Fiberglass wicks, Preferential flow, Monoliths.*

Nitrogen fertilizer has long been the mainstay of corn production throughout the United States. Yet technologies for accurately determining crop nitrogen requirements, controlling application rates, and for determining the fate of nitrogen applied in excess of crop needs have only recently been perfected. Since low nitrogen content can be the factor that limits the production of algal blooms, any transport of nitrogen from crop-producing areas might exacerbate agriculture's impact on ground and surface water. Nitrogen applied in excess of crop needs can be leached into groundwater by untimely

rainfall or irrigation, transported with subsurface drainage water, or contained in surface runoff flowing into streams, rivers, and lakes. Thirty states have recorded nitrate concentrations between 3 and 10 mg L⁻¹ from 68 aquifers (USDA, 1991). Agriculture in the upper Mississippi River basin has been linked to a large hypoxic zone in the Gulf of Mexico (Rabalais, 1992). With agriculture documented as a major source of nitrate contamination, it is crucial that steps be taken to limit transport of N from crop land. To accomplish this goal, farmers must know in advance whether the cropping systems they select will adversely affect ground and/or surface water quality.

Tillage practices (Kanwar et al., 1985; Dunn and Phillips, 1991), crop rotations (Owens et al., 1995; Kanwar et al., 1997), and nitrogen (N) placement techniques (Baker and Timmons, 1994; Clay et al., 1994; Baker et al., 1997) can influence water and nitrate-nitrogen (NO₃-N) movement through soil. In a summary of research conducted in Europe, Frede et al. (1994) showed that no-tillage cropping systems resulted in a significant increase in the number of earthworms and the percent of the soil volume occupied by biopores compared to conventional tillage. The increase in biopores led to increased infiltration capacity. During a six-year investigation of the hydrologic impacts of surface tillage, Dick et al. (1989) collected 55% of the water applied from no-till compared to 24% from conventionally tilled lysimeters. The influence of tillage

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was evident after three years of the study. Kanwar et al. (1985) found that more $\text{NO}_3\text{-N}$ was leached from a moldboard plow treatment than from a no-till treatment. Yet Weed and Kanwar (1996) reported 140 mm more drainage from ridge tillage, chisel plow, and no-till treatments when compared with moldboard plow. In one of the few studies aimed at estimating differences between soil resident nitrogen and surface applications, van Es et al. (1991) reported that leaching of soil-residual nitrogen was either not correlated or negatively correlated with drainage while surface applied nitrogen was highly correlated with drainage. Since most farmers in the midwestern United States still perform at least one secondary tillage operation prior to planting, the discrepancies in research results warranted additional evaluation of the impact of tillage on $\text{NO}_3\text{-N}$ leaching losses.

Baker and Timmons (1994) recovered more labeled ^{15}N from point-injector compared to surface-banded N treatments. Clay et al. (1994) reported greater leaching of $\text{NO}_3\text{-N}$ when anhydrous ammonia was knifed into the soil ridge compared with application in the interrow area. They concluded that the application slot remained intact if the anhydrous ammonia was applied on the ridge, while a similar slot in the interrow area would be closed by soil transported by surface runoff. Hamlett et al. (1990) found that liquid N applied on ridges was less likely to be leached than nitrogen applied to flat, tilled areas.

Based on previous research, Baker et al. (1997) combined a point injector with surface compaction above the N application zone in an effort to reduce $\text{NO}_3\text{-N}$ leaching losses. Bromide concentrations of drainage water from 0.76-m square soil monoliths for the treatments compacted around a point of injection were less than 15% of those for the uncompacted treatments. This work combined two application components to reduce water- $\text{NO}_3\text{-N}$ interaction: (1) the point injector limited the volume of soil that would contain N; and (2) compacting the soil above the application zone directed infiltrating water away from the N application zone. Subsequent investigations led to the development of an applicator that combined knife application with a smearing shoe, soil doming, and surface compaction components (Ressler et al., 1997). Field soil infiltration measurements with a constant head ring infiltrometer indicated that the infiltration rate was reduced by nearly half in the application zone compared to a conventional knife applicator.

Researchers using 250 to 300 mm diameter disturbed or undisturbed soil columns have cited preferential flow pathways to explain water fluxes that were greater than the soil saturated hydraulic conductivity (Booltink and Bouma, 1991; Singh and Kanwar, 1991). Shipitalo et al. (1990) found that only 17% of the soil volume contributed to drainage resulting from a simulated rainfall of 30 mm. By dividing the drainage collection device into small cells, they found that a single cell often accounted for 70% of the total leachate resulting from a 60 mm application. Nitrate losses were most significant for 10 mm h^{-1} rainfall events immediately following application. Bouma et al. (1982) recorded flow rates of 20 to 140 $\text{cm}^3 \text{min}^{-1}$ through individual worm holes that extended from the soil surface to the bottom of the soil column. Singh and Kanwar (1991) noted that some 300 mm diameter soil cores contained

worm holes while others did not. Beven and Germann (1981) suggested that representative elementary volumes (REV) be used to establish the soil sample size. Using their approach, soil samples of one-meter cubic or larger may be necessary to accurately study macropore flow. Based on these results, we concluded that a laboratory study of leaching losses required a much larger volume of soil than represented by 300 mm diameter columns.

Solute transport studies have been conducted using bromide, chloride, iodide, nitrate, fluorescent dyes, benzoic acids, and radioactive isotopes (Everts and Kanwar, 1990; Rice et al., 1991; Ghodrati and Jury, 1992). Chloride and bromide have been used as tracers in $\text{NO}_3\text{-N}$ leaching studies because they normally occur at low concentrations in most soils, their analysis is inexpensive, and they travel with leaching water similar to nitrate (Saffigna et al., 1977). Rice et al. (1991) applied four benzoic acid tracers and bromide to a sandy loam soil to evaluate solute movement under furrow irrigated conditions. Using a water balance approach, they found that tracer flow velocity was 2 to 2.5 times greater than velocities predicted by a piston flow model. Though analysis costs are greater, these organic acid tracers do not occur naturally in soils. Whitehead (1974) found that in soils with pH in the range of 5.5 to 7, iodide sorption to ferric and aluminum oxides decreased to near zero. Therefore, for many midwest soils, potential sorption to ferric and aluminum oxides should not prevent the use of iodide as a tracer. However, iodide degrades with time to elemental iodine due to microbial activity. Despite research evidence suggesting that iodide would be an acceptable tracer, we decided to verify the suitability of using iodide by conducting an iodide degradation study using soils from the research site.

Spatial variation in leachate has been documented under field conditions (Andreini and Steenhuis, 1990; Heuvelman and McInnes, 1997) and under laboratory conditions (Aburime et al., 1995; Edwards et al., 1992) using tracer applications to the soil surface prior to a rainfall event. Heuvelman and McInnes (1997) reported spatially normalized water fluxes with coefficients of variation of less than 50% at depths of 0.3 m to 150% at depths between 0.9 and 1.2 m. This indicates that water converged into fewer flow paths with increased soil depth. Aburime et al. (1995) recorded substantial spatial variation of alachlor and atrazine leaching from undisturbed soil columns after a 10 mm d^{-1} water application that resulted in about 500 mm of drainage. Kung (1993) used a soil tank to study impact of a soil texture on the downward movement of percolating water. He noted that when a lens of different texture was placed at a 15° angle from horizontal, percolating water flowed along the interface between two soil textures rather than continuing downward through the different texture. These research efforts show that preferential flow pathways may take on many forms depending on the soil texture, structure, and way the soil formed on the landscape. Hence, it was decided to combine fiberglass wicks with a grid cell collector in an effort to record the leaching variation that existed at the research site.

OBJECTIVES

Most research has concentrated on one or two tracer application methods and two or three tillage systems, but more importantly, soil columns were too small to

accurately depict field-scale variation. This leaves uncertainty about how other application methods would have performed and whether larger soil columns would produce similar results. Thus, the overall objective was to evaluate the response of three tracer application methods simultaneously using 1 m cubic soil monoliths that had a long term history of three different tillage and planting systems. The specific objectives of this research were to: (1) determine the effect of preplant tillage on the spatial distribution of drainage and soil resident nitrate losses; and (2) determine the effect of water application immediately following tracer application on the spatial distribution of leachate resulting from three surface applied tracers.

MATERIALS AND METHODS

This study was conducted in the hydraulics laboratory of the Agricultural and Biosystems Engineering Department at Iowa State University in Ames, Iowa. Eight, 1-m cubic (1 m × 1 m × 1 m) undisturbed soil monoliths were collected from research plots located near Nashua, Iowa, located approximately 190 km northeast of Ames, Iowa. The research plots had received consistent tillage practices and were in a corn-soybean rotation over the 15-year period prior to collection of the monoliths. Plow and chisel tillage treatments were imposed on 2-3 April 1992 followed by a light field cultivator pass on 12 May immediately prior to planting soybeans in 0.76 m rows. Soil areas approximately 2.0 m square were covered with plastic after planting to maintain soil surface conditions. The monoliths were collected from the field between 15 June and 30 August 1992.

The dominant soil at the site was a Kenyon silt loam (fine-loamy, mixed, mesic *Typic Hapludoll*). Following excavation of the soil monoliths and over 15 years of research at the site, an in-depth soils map was completed. According to the more detailed soil map, some monoliths were collected from areas mapped as Floyd loam (fine-loamy, mixed, mesic *Aquic Hapludoll*), others a Readlyn loam (fine-loamy, mixed, mesic *Aquic Hapludoll*) (Logsdon et al., 1993). These soils are classified as poorly to moderately well drained. The main differences in the soil profiles were that the Readlyn soil had a 530 mm deep silty clay loam A and B horizon and the Floyd soil has a 300 mm deep sandy loam B22 horizon. The remainder of each profile consisted of loam textured soils (USDA-NRCS, 1977). Table 2 lists the soil mapping unit for each monolith, Soil_m. Other pertinent soil physical and hydraulic properties for the soils studied are presented in Singh (1994).

Complete details of the soil monolith excavation and collection procedures are presented in Kranz et al. (1998). Three monoliths were to be collected from the moldboard plow, chisel plow, and ridge tillage treatments for a total of nine monoliths (3 tillage treatments × 3 replicates = 9). However, the collection procedure caused the soil column to collapse on replicate three of the ridge tillage treatment. Since duplicate sampling areas were not established after planting soybeans, the option to collect an undisturbed soil monolith from another site in the field did not exist.

IODIDE DEGRADATION STUDY

To verify that iodide was a suitable tracer for our conditions, an iodide degradation was conducted using soil from the 0 to 150 mm depth. A standard solute was created using 216 g of laboratory grade potassium iodide mixed with 0.7 L of tap water. Spiked soil samples were prepared by adding 20 mL of a 309 mg L⁻¹ iodide solution to 85 g of oven-dried soil. This made the combination equivalent to 55 mg L⁻¹ on a dry soil basis. Forty samples were prepared consisting of eight sets of five samples each. Each set of samples contained three replications of the soil-solute mixture, one blank soil sample (no iodide), and one tap water. Tap water was included to verify that the tap water did not contain iodide. The samples were placed in a covered fish aquarium to maintain soil moisture conditions.

One set of samples was removed from the aquarium for analysis 1, 2, 4, 5, 6, 7, 18, and 30 days after the soil-solute mixture was created. Chemical analysis included adding 400 mL of distilled-deionized water, placing the sample on a magnetic stirrer, separating solids using a centrifuge, passing the extract through filter paper and chemical analysis by ion chromatography. Iodide concentration versus time data were analyzed using a curve-fitting routine.

Results from the iodide degradation study indicated that iodide has a half-life of about five days (t) when iodide is thoroughly mixed with the soil. After two days, the concentration (C) would be about 80% of the tracer amount applied to the soil $C = 46.8 e^{(-0.121t)}$, $r^2 = 0.83$). Based on these results, and the fact that iodide was to be applied via the irrigation water which limited contact with soil particles, iodide should be an acceptable tracer for NO₃-N for studies that occur over a period of 24 to 36 h. Since our work was completed, Shepard et al. (1996) summarized various research efforts that indicated that chlorine interfered with sorption of iodide. Thus, since we also applied potassium chloride, degradation should have been slower than indicated by the test results reported above.

WATER APPLICATION

Water was applied to the soil surface of each monolith using a rainfall simulator modeled after the Rocky Mountain infiltrometer (Dortignac, 1951). A detailed discussion of the test stand used during rainfall simulations is presented in Kranz et al. (1998). Water was applied at a rate of approximately 33 mm h⁻¹ for all tests. The application rate was controlled by a needle valve, bypass pressure regulating valve, and readings from a positive displacement flow meter (Kranz et al., 1998). Application uniformity tests produced a Christiansen Uniformity Coefficient of approximately 90%. Some ponding was noted for each monolith.

Water application was limited to a 0.8 m × 0.8 m area (0.64 m²) of the soil surface by a galvanized steel shroud with 300 mm high sidewalls which forced all water applied to the soil surface to infiltrate into the soil. The shroud was pushed into the soil 25 to 50 mm to prevent water from passing out of the application area. Water collection troughs, attached to the top outer edge of the shroud, collected water not meant for the soil surface. Thin sheets of polyethylene plastic film were hung from the rainfall simulator panel to ensure that all water leaving the panel landed on the soil or in the collection troughs. Each section

of the trough was attached to the shroud with a slight slope to encourage drainage to a single collection point where the volume collected was monitored at regular intervals.

Each monolith received a water application of approximately 150 mm 24 h prior to tracer application to insure that its soil was near field capacity. Soil surface conditions were preserved by a double layer of fiberglass screen which absorbed water droplet impact. The application water was obtained from a rural well and had a mean anion concentration of 3.8 mg L⁻¹ chloride, 1.2 mg L⁻¹ bromide, and 0.0 mg L⁻¹ iodide. In all cases, leachate was collected from all but two to three grid positions following this water application, and few were still draining prior to tracer application.

TRACER APPLICATION

Anion tracers were applied to mimic N applied using a slot with surface compaction method (SLOT), surface broadcast (BROAD), and with water (WATER). Tracers were applied sequentially to each monolith approximately 24 h after the initial water application. Tracers were applied in the following order: (1) bromide was applied in the SLOT treatment; (2) chloride in the BROAD treatment; and (3) iodide was applied as the WATER treatment to simulate NO₃-N applied via irrigation. Each tracer was applied at a rate equal to approximately 225 kg ha⁻¹. This required an application of approximately 33.5 g of potassium bromide, 47.2 g of potassium chloride, and 29.5 g of potassium iodide to each monolith.

The SLOT (Br) treatment was similar to the concept presented by Baker et al. (1997). The treatment consisted of opening a slot across the midpoint of the monolith and approximately at the top of the ridge, adding the potassium bromide tracer to the slot, covering the slot with loose soil, and compacting the soil over the application zone. Soil compaction over the slot was achieved using two 203 mm diameter × 38 mm wide wagon wheels positioned at 45° from vertical, and a 20 kg steel weight. The apparatus was moved across the monolith, making six passes, directly above the slot opening (Kranz et al., 1998).

Potassium bromide solution was applied to the slot using a plastic specimen washing bottle. The specimen bottle was moved by hand across the soil surface at nearly constant speed. Five to six passes were made with the bottle resulting in an application zone approximately 50 mm wide. Paper towels were placed at the edge of the monolith to collect the solute that would otherwise be applied to the plaster-of-paris. The towels were weighed before and after the application to determine the mass of the tracer reaching the soil.

The BROAD (Cl) treatment using potassium chloride tracer was applied to the soil surface using four sprayer nozzles mounted on a small spray boom. Pressure was supplied manually by a hand spray can attached to the spray nozzles. The spray boom was moved back and forth across the monolith until 1.5 L of the solute was applied to the soil surface. This required approximately six passes across the monolith. As before, paper towels were used to collect the spray that would otherwise have been delivered to the plaster-of-paris at the edge of the monolith. The towels were weighed before and after the application to determine the mass of tracer reaching the soil.

The WATER (I) treatment using potassium iodide was applied with the first irrigation event of approximately 100 mm of water. Potassium iodide was mixed in a polyethylene container and then added to approximately 100 L of water in a holding tank (Kranz et al., 1998). The mixture was circulated in the tank prior to starting the water application. Thus, iodide was applied during the application of approximately 100 mm of water.

The application rate and depth of water applied during the initial rainfall simulated a 10 year, 6 h storm for central Iowa. Twenty-four hours later, an additional 430 mm were applied to establish tracer breakthrough curves with additional water application. This brought the total water application to 530 mm which is approximately equal to one pore volume for these soils.

Leachate samples were collected during and immediately following water application using a fiberglass wick sampler modeled after Boll et al. (1992). The sampler was constructed of ultra high molecular weight plastic with 12 to 230 mm wide buffer cells positioned around the perimeter of the grid cell collector. Under the center of the monolith, a 6 × 6 matrix of 90 mm × 90 mm grid cells defined the main sample area. Leachate samples were collected into 0.75 L glass jars placed in a grid box mounted on a cart. The cart was on wheels that allowed sets of sample jars to be easily exchanged at each sampling time. Sample jars were recycled during the simulation runs after being triple rinsed with distilled-deionized water in a portable dishwashing machine. Subsamples were collected from each grid cell and the buffer cells using 3 mL polyethylene test tubes. Test tubes were refrigerated at approximately 5°C until laboratory analysis could be conducted during a one-year period.

Leachate samples were collected beginning with the first flush of drainage water and continued for 24 h after water application was completed. The first flush was identified as the time when approximately 20% of the grid points were draining. The water sample collection scheme was developed to allow flexibility in selecting which sampling times would be analyzed for anion concentration. Approximately eight sets of samples (at approximately 0.1 pore volume intervals) were analyzed for chloride, bromide, and iodide for each grid cell using an ion chromatograph (DIONEX IonPac® AG11 Guard Column). Incremental leaching losses for each grid cell were determined by multiplying the sample concentration by the leachate volume collected. Flow-weighted concentrations were calculated for each sampling time by dividing the sum of concentration times flow by the total flow for the time period between samples.

Calculation of a mean concentration for each grid point and tracer would serve the purpose of presenting all the data in one graph of leaching loss for each tracer. However, in doing so the variation that existed in each monolith would be masked since spatial variation does not occur in a grid arrangement. Consequently, one monolith from each tillage treatment was selected to depict the variation in leaching that was recorded. The same three monoliths will be used when discussing each of the tracer applications since they portray results most effectively for all tracers.

The statistical design was a split-plot with tillage treatment as the whole plot and tracer application method as the subplot. Analysis was performed using the Mixed

Model procedures (Littell, 1996). The Kolmogorov-Smirnov one-sided analysis procedures were used to evaluate differences in cumulative drainage distribution curves (Conover, 1980).

RESULTS AND DISCUSSION

Soil data collected in the field from the area surrounding each monolith showed that soil bulk density increased with depth from 1.49 Mg m⁻³ at the 0.1 m depth to 1.66 Mg m⁻³ at 0.7 m (table 1). Bulk densities for the 0.1 and 0.3 m depths were significantly lower than those recorded for depths below 0.3 m. This increase in bulk density with depth is attributed to an increase in sand content with depth (USDA, 1977). Mean saturated hydraulic conductivity ranged from 213 mm h⁻¹ at the 0.1 m depth to 450 mm h⁻¹ at the 0.7 m depth. Mean conductivities recorded for the 0.3, 0.5, and 0.9 m depths were 276, 162, and 271 mm h⁻¹, respectively. Soil from the ridge tillage treatment had the greatest mean conductivity at the 0.7 m depth (802 mm h⁻¹), and the greatest conductivity for the 1 m profile (351 mm h⁻¹). These data indicate that water should pass through the soil most rapidly in the ridge till treatment.

LEACHATE DISTRIBUTION

One potential artifact of applying three tracer treatments to a single monolith was the potential that the SLOT (Br) treatment might affect the flow of water moving through the soil. If water flow was altered, it could skew the effect of the BROAD (Cl) and WATER (I) treatments. Figures 1a through 1c present drainage depths collected from each grid cell for one monolith of each tillage treatment. If the SLOT (Br) treatment had affected infiltration, drainage collected from cells located in columns C and D should be considerably less than or greater than the surrounding cells. Statistical analysis was performed to determine if drainage from columns C and D were different than B and E or A and F. Across treatments, no significant differences were found in drainage ($p < 0.05$). Analysis identified only one case where a significant difference existed between columns C and D and the other columns. For the second replicate of the chisel plow treatment (CPR2), columns A and F were different ($p < 0.05$). Columns A and F were

Table 1. Summary of soil physical properties*

Soil Depth (m)	Bulk Density (Mg m ⁻³)			Means by Depth (Mg m ⁻³)
	Chisel Plow	Mold-board Plow	Ridge Tillage	
0.1	1.47a	1.51a	1.49a	1.49a
0.3	1.54ac	1.49a	1.50a	1.51a
0.5	1.60bc	1.61ac	1.60ac	1.60b
0.7	1.58ac	1.65bc	1.66bc	1.63b
0.9	1.65bc	1.62bc	1.70bc	1.66b
Treatment means	1.57	1.59	1.58	1.58
n	3	3	2	

Soil Depth (m)	Saturated Hydraulic Conductivity (mm h ⁻¹)			Means by Depth (mm h ⁻¹)
	Chisel Plow	Mold-board Plow	Ridge Tillage	
0.1	41	29	570	213
0.3	161	401	267	276
0.5	302	74	116	162
0.7	168	381	802	450
0.9	787	26	1	271
Treatment means	292	182	351	275
n	3	3	2	

* Data within each column followed by the same letter are not significantly different at the $p < 0.05$ significance level. Absence of a letter indicates lack of statistically significant differences.

found to be different than columns B and E for replicate one of the chisel plow treatment.

At least two explanations of how drainage could have occurred are plausible. At the surface, infiltration could have been restricted by the SLOT (Br) treatment, and once water moved beyond the tillage layer, water could have moved by horizontal dispersion back into the area directly below the slot. The alternative is that the SLOT (Br) treatment had little or no effect on water flow. Based on statistical analysis of drainage data, the SLOT (Br) treatment did not significantly impact water movement.

Water application and total drainage collected for the 100 mm event are presented in table 2. Mean water application for all tests was 101 mm with a range from 95 to 107 mm of water which is well within the sensitivity of the control valve adjustment. On average, drainage for the

Table 2. Summary of water application, and NO₃-N leaching loss information from each soil monolith

Water (mm)*	Chisel Plow				Moldboard Plow				Ridge Tillage			Overall Mean
	CPR1	CPR2	CPR3	Mean	MPR1	MPR2	MPR3	Mean	RTR1	RTR2	Mean	
Soil _m	Floyd	Kenyon	Floyd	103	Readlyn	Floyd	Readlyn	98	Floyd	Floyd	103	101
To soil surface	104	102	102	103	n/a†	101	95	98	100	107	103	101
From buffer cells	70	47	63	71	68	58	75	67	70	80	75	67
From grid cells	85	76	51	71	67	89	54	70	74	66	70	70
Grid cell CV (%)	82	77	51	70	81	55	76	70	65	49	57	66
Collection efficiency (%)‡	91	98	77	87	n/a†	97	90	93	91	89	90	90
NO ₃ -N (kg ha ⁻¹)§												
SOIL _b	47.8	84.9	84.9	63.7	23.9	n/a	77.3	54.5	39.3	42.1	40.7	53.0
Grid cell mean	24.9	18.3	13.9	19.0	0.4	14.5	4.4	6.4	13.1	17.7	15.4	13.6
Grid cell range	42.9	61.6	31.8	45.4	2.7	42.7	23.8	23.1	42.7	23.2	32.9	33.8
Grid cell CV (%)	47.0	82.3	83.2	70.8	138.5	60.6	128.2	109.1	105.4	38.3	71.8	83.9
SOIL _e	22.9	66.6	n/a†	44.7	23.4	n/a	72.9	48.1	26.2	24.4	25.3	39.4

* Water balance data have units of millimeters unless otherwise indicated.

† Data collection equipment error or data could not be collected.

‡ Collection efficiency equal to depth collected from grid and buffer cells divided by depth applied to the soil.

§ Nitrogen balance data have units of kg ha⁻¹ unless otherwise indicated.

|| Field soil nitrate prior to collection of the monoliths (SOIL_b) and within the monolith after the study (SOIL_e).

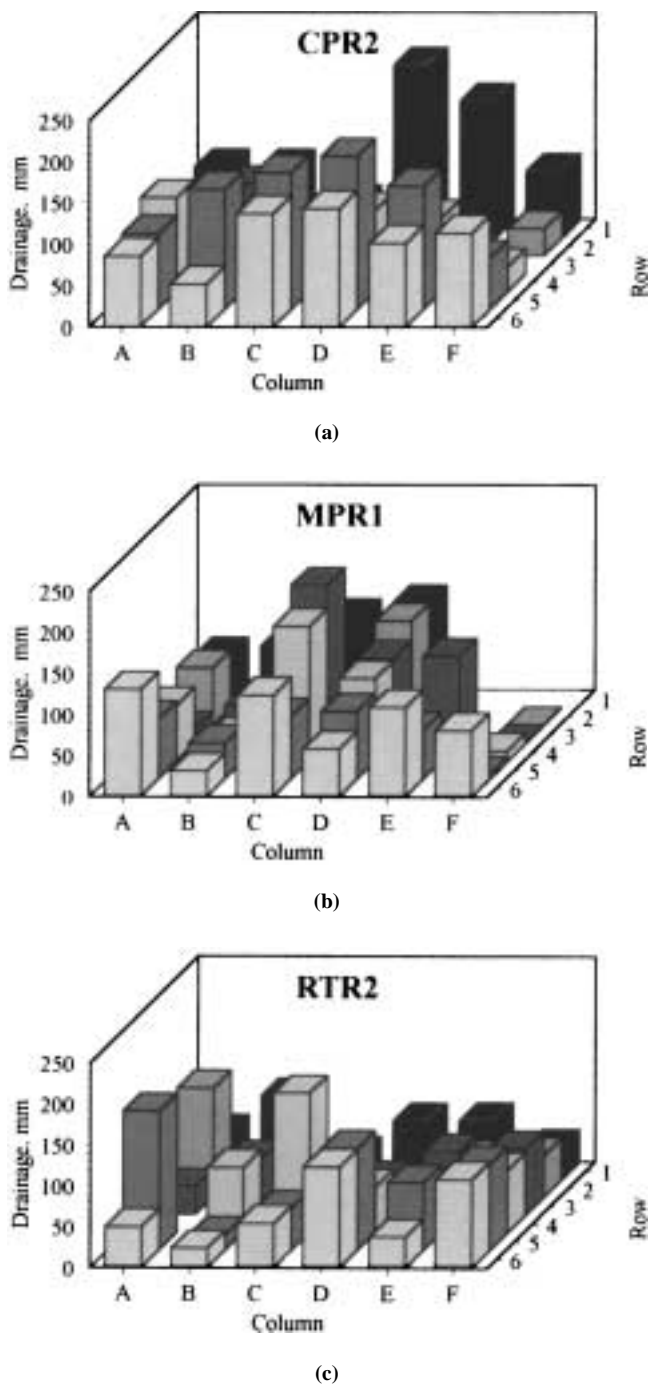


Figure 1—Spatial distribution of drainage resulting from a 100 mm water application for the CPR2, MPR1, and RTR2 monoliths.

100 mm application for the chisel plow, moldboard plow, and ridge tillage treatments were between 70 and 71 mm. The mean for the range in drainage among individual grid cells was between 129 and 208 mm (table 3). Drainage for the 430 mm application averaged, 319, 313, and 256 mm from the chisel plow, moldboard plow, ridge tillage treatments, respectively (table 4). Since water application data showed nearly equal water application depths, some of the water applied must have remained in the soil at the end of the study.

The greatest variation in mean drainage came from the water collected in the grid cell sampler (table 2). The

overall treatment mean was 70 mm with a range of 50 to 89 mm. The coefficient of variation for the leachate recovered in the grid sampler ranged from 49% to 81%. These differences likely originated from the volume of water that moved horizontally in the soil into the buffer cells or water that remained in the soil at the end of the test. The mean volume collected in the buffer cells was 67 mm with a range of 47 to 80 mm. This range would account for approximately 86% of the difference between water applied to the soil surface and water caught in the grid cell sampler. An additional 10 to 15 mm of water remained in the soil or was otherwise unaccounted for by the sampling protocol. Despite these differences, on average, 90% of the water applied to the soil surface was collected at the bottom of each monolith.

Existence of preferential flow pathways implies that some grid cells will produce more drainage than others. Thus, if cumulative drainage versus cumulative soil surface area curves are above the 1:1 line, preferential flow exists. Figures 2a through 2c present cumulative distributions from the 100 mm water application for each monolith. Based on the Kolmogorov-Smirnov analysis of the distribution curves, significant differences were found between monoliths CPR1 and CPR3 within the chisel plow tillage treatment, but only at the $p < 0.20$ level. No significant differences among tillage treatments were found when mean tillage treatment values were compared. This indicates that no differences in drainage existed among monoliths regardless of soil surface tillage treatment.

NITRATE LEACHING LOSSES

The mean $\text{NO}_3\text{-N}$ loss after a 100 mm water application was approximately 14 kg ha^{-1} with a range of 0.4 to 25 kg ha^{-1} (table 3). No significant differences in $\text{NO}_3\text{-N}$ losses were identified among tillage treatments. However, some trends seemed to appear. On average, the moldboard plow treatment resulted in the least $\text{NO}_3\text{-N}$ loss despite recording the greatest drainage. The $\text{NO}_3\text{-N}$ loss recorded for the ridge tillage and chisel plow treatments was 15 kg N ha^{-1} and 19 kg N ha^{-1} , respectively. Since mean drainage was similar among treatments, more water flowing through the moldboard plow monoliths must have bypassed nitrogen stored in the soil matrix compared to the other tillage treatments.

The spatial distribution of $\text{NO}_3\text{-N}$ leaching losses are presented in figures 3a through 3c. Leaching losses were not found to be spatially oriented suggesting that preferential flow pathways were randomly distributed within the soil. Visually, with the exception of one grid cell, figure 3c depicted more consistency among grid cells than in figure 3a or 3b. The CVs calculated for the CPR2, MPR1, and RTR2 monoliths were 82, 138, and 38%, respectively (table 2). A large number of zero $\text{NO}_3\text{-N}$ leaching losses recorded for the MPR1 monolith resulted in high CV value. Leaching losses for the CPR2 monolith were greater than either the MPR1 or RTR2 monoliths. High variation in $\text{NO}_3\text{-N}$ leaching losses suggests that preferential flow pathways are present and actively transport water and nutrients through the root zone. Surface tillage appears to have little impact on the mass of nutrients transported through the soil.

Table 3. Summary of tracer leaching losses for the BROAD (Cl), SLOT (Br), and WATER (I) tracer application methods from each monolith following 100 mm of water application

Tracer	CPR1	CPR2	CPR3	Mean	MPR1	MPR2	MPR3	Mean	RTR1	RTR2	Mean
Cl (kg ha ⁻¹)											
Mean *	16.1	11.4	5.6	11.0	6.1	23.1	7.9	12.4	14.6	12.6	13.6
Range *	50.2	30.2	17.5	32.6	17.3	98.7	54.9	56.9	30.2	41.4	23.9
CV (%)	65.8	81.6	89.3	78.9	86.9	78.4	139.2	80.2	58.2	79.4	68.8
Br (kg ha ⁻¹)											
Mean *	0.7	8.1	5.5	4.7	7.9	56.1	0.2	21.4	3.6	0.7	2.1
Range *	4.2	60.0	40.4	34.9	49.0	225.5	1.4	92.0	44.6	3.1	23.8
CV (%)	142.9	188.9	167.3	166.4	183.5	107.3	145.0	145.3	241.7	114.3	178.0
Iodide (kg ha ⁻¹)											
Mean *	3.9	2.9	0.8	2.5	3.7	12.0	0.8	5.5	2.5	2.0	2.2
Range *	20.6	12.5	4.4	12.5	37.9	33.7	4.5	25.4	12.7	17.7	15.1
CV (%)	141.0	113.8	137.5	130.8	200.0	65.0	150.0	138.3	116.0	155.0	135.5

* Data are presented are means of 36 grid cells.

Table 4. Summary of drainage and leaching losses for the BROAD (Cl), SLOT (Br), and WATER (I) tracer application methods from each monolith following 430 mm of water application

Tracer	CPR1	CPR2	CPR3	Mean	MPR1	MPR2	MPR3	Mean	RTR1	RTR2	Mean
Drainage (mm)											
Mean*	468	263	226	319	329	436	174	313	300	214	257
Range	1464	1103	830	1132	1124	1037	461	255	814	583	808
CV (%)	71	88	88	82	86	58	77	74	70	65	68
Cl (kg ha ⁻¹)											
Mean *	33.5	17.6	8.5	19.9	20.2	29.6	16.2	22.0	26.2	25.3	25.7
Range	87.7	57.9	21.0	55.5	55.7	117.7	80.0	84.5	61.5	74.5	68.0
CV (%)	60.6	80.1	69.4	70.0	73.8	70.9	101.9	82.2	53.1	70.8	61.9
Br (kg ha ⁻¹)											
Mean *	42.2	33.2	54.5	43.3	71.6	80.8	17.4	56.6	21.9	18.3	20.1
Range	171.0	209.0	384.9	255.0	348.3	336.6	90.7	258.5	189.9	135.2	162.5
CV (%)	122.3	148.2	140.2	136.9	140.6	103.0	149.4	131.0	196.8	154.6	175.7
Iodide (kg ha ⁻¹)											
Mean *	11.2	9.2	5.7	8.7	14.1	16.4	3.9	11.2	6.3	9.9	8.1
Range	25.9	30.8	20.3	25.7	60.9	34.3	11.9	35.7	16.9	27.6	36.0
CV (%)	61.6	83.7	93.0	79.4	92.9	56.7	87.2	78.9	66.7	73.7	70.0

* Data are presented are means of 36 grid cells.

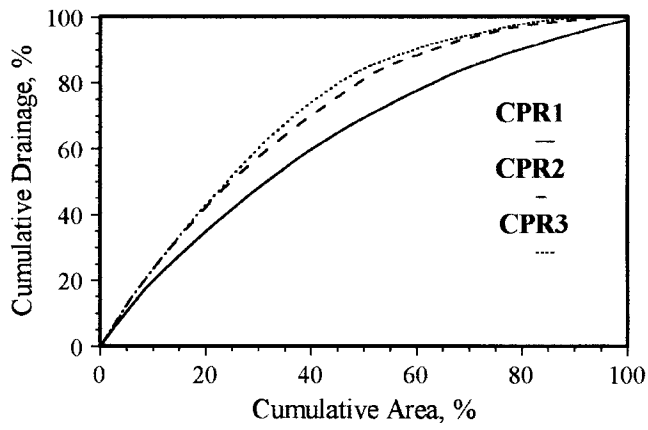
TRACER LOSSES

Table 3 summarizes the mass of leaching losses recorded for each tracer for the 100 mm water application and table 4 presents the same data for the 430 mm water application that followed approximately 24 h later. No significant differences were found among treatments for either water application event ($p < 0.05$). Lack of significance among the tracer treatments is attributed to data variation. Again, some trends were evident.

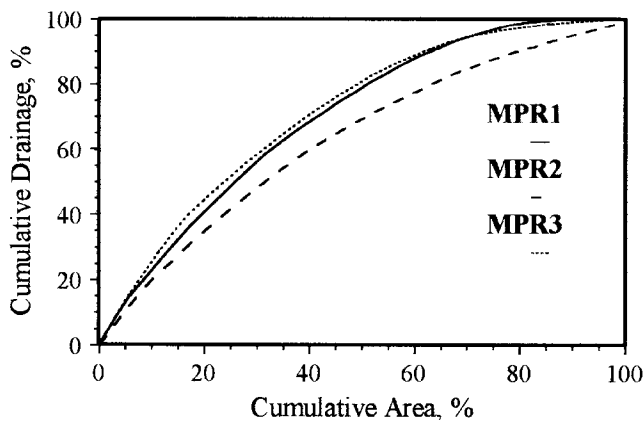
The overall means for each tracer and water application event suggest that applying the tracer with an irrigation system tended to reduce leaching losses (tables 3 and 4). Iodide losses for the chisel plow and moldboard plow treatments were less than half that of the other tracers. Iodide loss from the ridge tillage treatment was nearly equal to the bromide application method, but only about one-sixth that recorded for the chloride application method. The bromide tracer (SLOT)-moldboard plow combination tended to produce greater leaching losses than the other two tillage treatments. As an example, the SLOT-moldboard plow treatment monoliths had a mean range in bromide leaching loss of 92 kg ha⁻¹ and a mean leaching loss of 21 kg ha⁻¹ following 100 mm of water application.

The mean was up to 10 times greater and the range was up to three times greater than the other tillage treatments. The large range in bromide leaching losses for the MPR2 monolith suggests that some preferential flow pathways were located directly below the application zone. For the 430 mm water application, the MPR1 and MPR2 monoliths produced the greatest mass of bromide (SLOT treatment). Hence, though tillage practice had minimal impact on drainage, data suggest that applying the tracer in a slot should be avoided if the field tillage treatment is moldboard plowing.

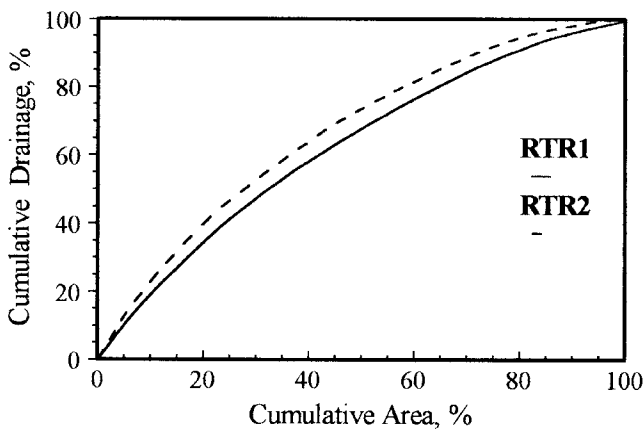
The 430 mm water application flushed more of the SLOT (Br) applied tracer into the collector than from the BROAD (Cl) or WATER (I) treatments. This is shown best in the overall means for leaching loss for each treatment (table 4). While leaching loss from the BROAD (Cl) treatment increased by 10 kg ha⁻¹, the SLOT (Br) treatment increased by 30 kg ha⁻¹ (table 4). Thus, an additional 20 kg ha⁻¹ was lost from the SLOT (Br) treatment. In the absence of sufficient surface compaction or doming of the soil to alter water flow, greater leaching loss would likely occur from slot treatments than broadcast type treatments.



(a)



(b)

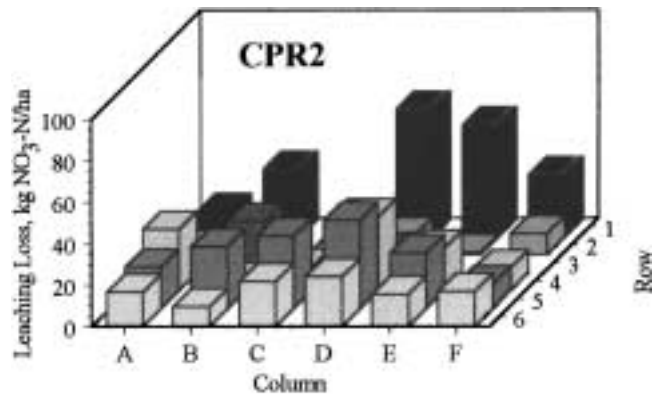


(c)

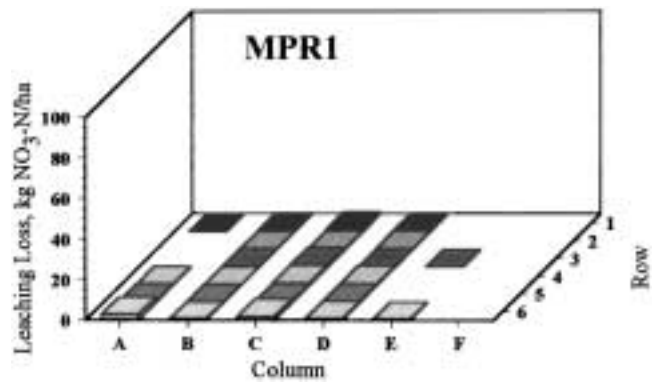
Figure 2—Cumulative drainage distribution curves resulting from a 100 mm water application to the chisel plow (a), moldboard plow (b), and ridge tillage treatments (c).

SPATIAL VARIATION

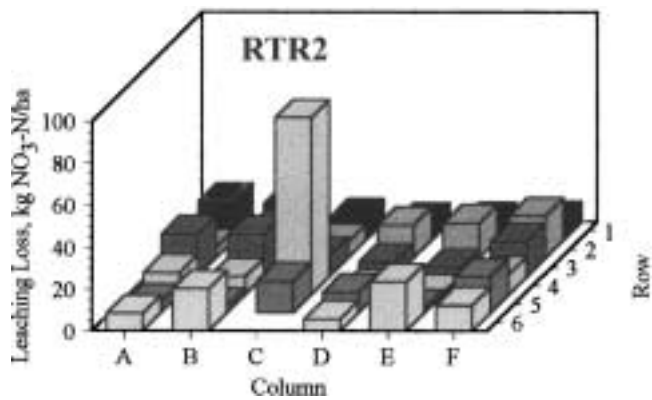
The effect of tracer application method recorded from the grid cell collector unit is presented in figures 4 through 6 by application method. These bar charts present leaching losses for the same three monoliths used in the discussion of variation in drainage water and NO₃-N leaching losses. The most notable features are that leaching losses for the BROAD (C1) (figs. 4a,b,c) and WATER (I) treatments



(a)



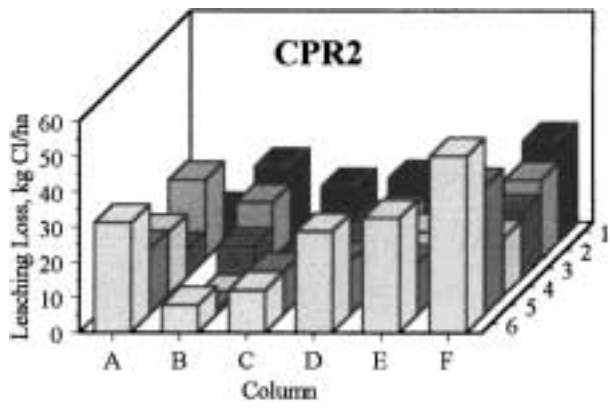
(b)



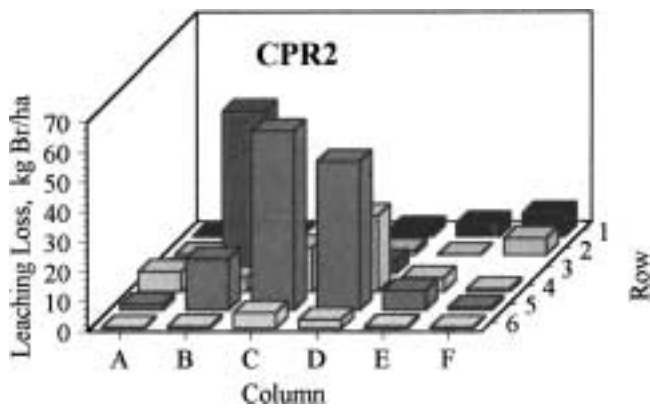
(c)

Figure 3—Spatial distribution of nitrate-nitrogen leaching losses resulting from a 100 mm water application for the CPR2, MPR1, and RTR2 monoliths.

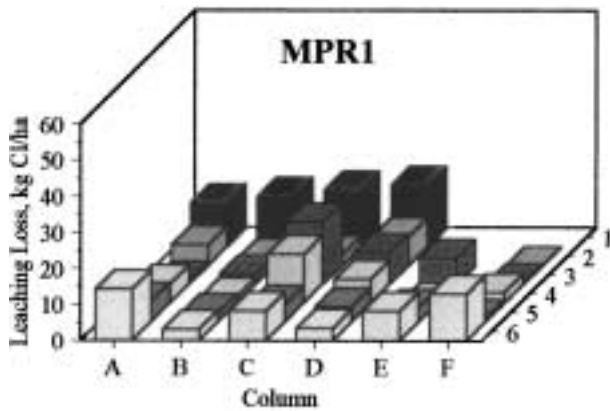
(figs. 6a,b,c) tended to follow closely the drainage results. Where drainage was high, leaching losses were also high. However, the SLOT (Br) treatment (figs. 5a,b,c) produced a distinctive bromide leaching pattern directly below the application zone. Most of the bromide tracer reaching the bottom of the box was contained in a band across the monolith; slightly more than two cells wide. Since the bromide tracer was placed in a slot about 30 to 50 mm wide just below the soil surface, the tracer moved laterally only about 100 to 150 mm while traveling a distance of about 900 mm through the soil profile. Analysis performed



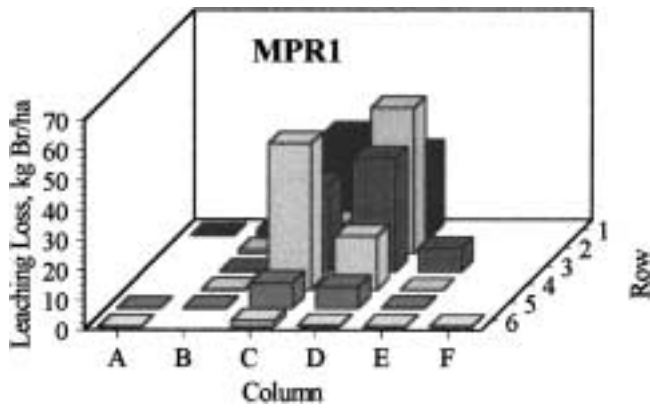
(a)



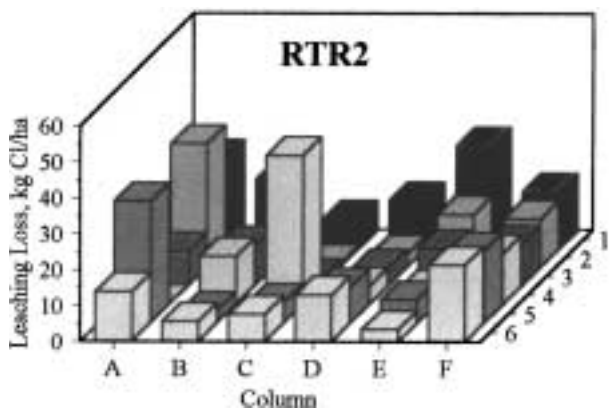
(a)



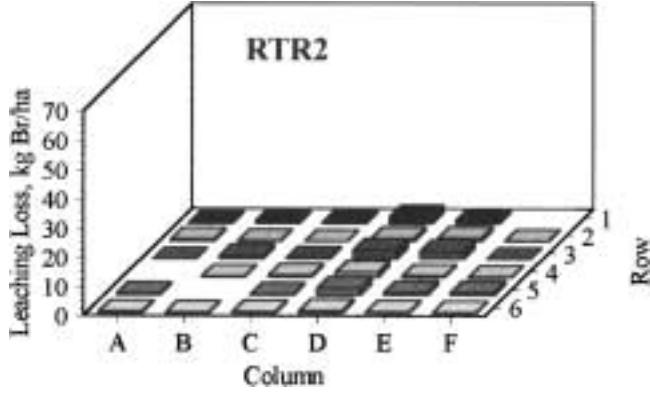
(b)



(b)



(c)



(c)

Figure 4—Spatial distribution of leaching loss for the BROAD (C1) treatment resulting from a 100 mm water application for the CPR2, MPR1, and RTR2 monoliths.

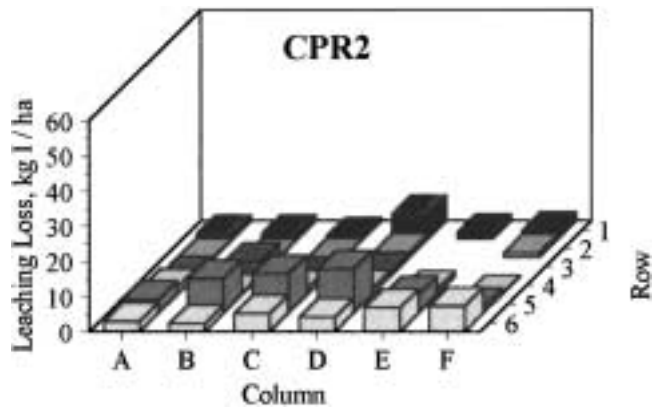
Figure 5—Spatial distribution of leaching loss for the SLOT (Br) treatment resulting from a 100 mm water application for the CPR2, MPR1, and RTR2 monoliths.

to confirm differences between columns C and D together and columns A, B, E or F found differences in only three of the eight monoliths. Differences were indicated for monolith CPR1 and CPR2 but not CPR3. For the moldboard plow treatments, only the MPR3 monolith produced significant differences. No differences were noted for ridge tillage treatments. This lack of lateral movement supports the hypothesis by Baker et al. (1997) that if applied water can be diverted around a narrow

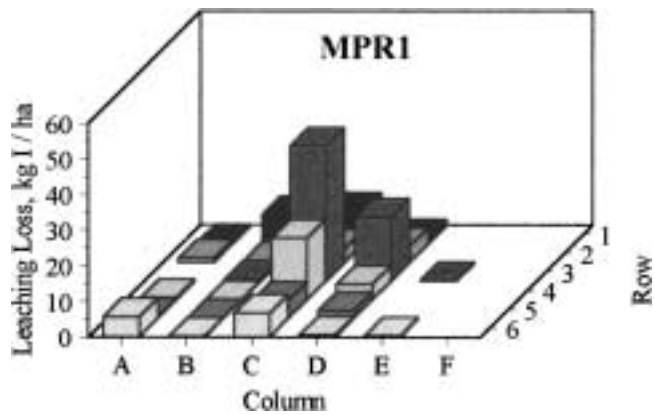
horizontal band above the N application zone, NO₃-N leaching loss might be reduced.

FLOW-WEIGHTED CONCENTRATIONS

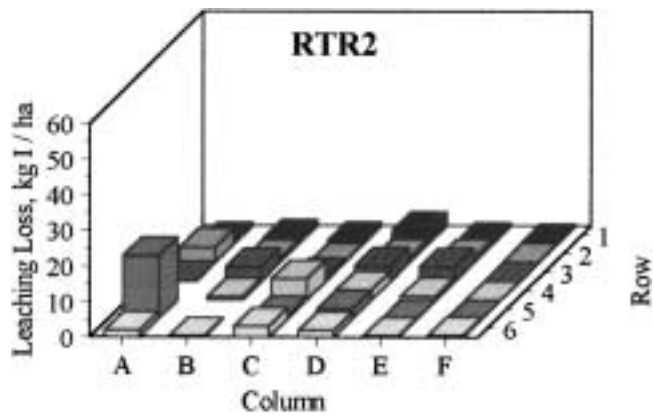
Figures 7 through 10 present flow-weighted average tracer concentrations for each tillage treatment by application method. Flow-weighted average NO₃-N concentrations are presented in figures 7a through 7c for the chisel plow, moldboard plow, and ridge-tillage treatments, respectively. Unlike the discussion of spatial



(a)



(b)

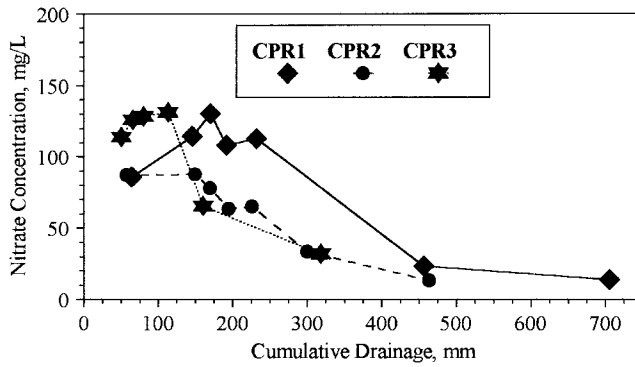


(c)

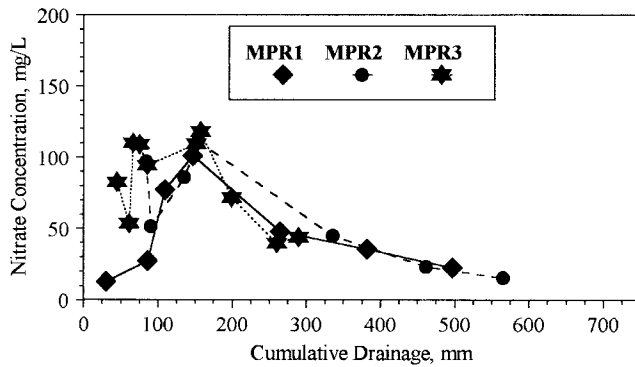
Figure 6—Spatial distribution of leaching loss for the WATER (I) treatment resulting from a 100 mm water application for the CPR2, MPRI, and RTR2 monoliths.

distribution of nitrate leaching losses, these figures include data from the second water application event and all replicates. This was necessary to show the trend in the data well beyond the drainage recorded for a single 100 mm water application.

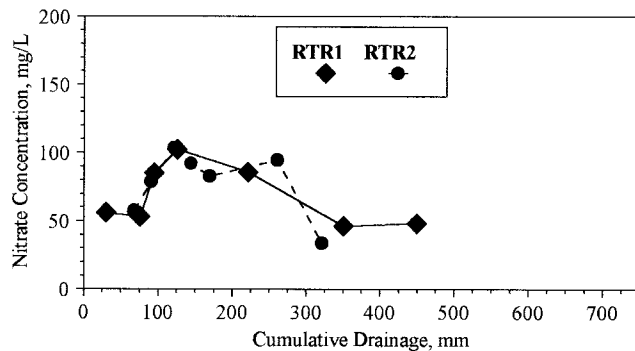
Results for the chisel plow treatment showed trends in $\text{NO}_3\text{-N}$ concentration that peaked at approximately 130 mg L^{-1} for monoliths CPR1 and CPR3 (fig. 7a). The peak $\text{NO}_3\text{-N}$ concentration occurred after a cumulative drainage



(a)



(b)



(c)

Figure 7—Trends in nitrate-nitrogen concentration for drainage resulting from approximately 530 mm of water application for the chisel plow (a), moldboard plow (b), and ridge tillage treatments (c).

of between 100 and 170 mm of water. Monolith CPR2 shows no major peaks in concentration, however, the samples analyzed may have missed the peak $\text{NO}_3\text{-N}$ concentration between the first and second samples (fig. 7a). If so, peaks for all replications would occur after about the same amount of drainage. Though the absolute peak may have been missed, the recorded peak $\text{NO}_3\text{-N}$ concentrations for CPR2 occurred following 68 mm of drainage. The decreasing portion of the curve corresponds well among replications with concentrations declining to approximately 15 mg L^{-1} .

Nitrate concentration peaks recorded for the moldboard plow treatment for monoliths MPR1 and MPR2 occurred following 150 mm of drainage, similar to the chisel plow

treatment (fig. 7b). However, the peak concentrations were between 101 and 111 mg L⁻¹ which were 20 to 30 mg L⁻¹ less than those recorded for the chisel plow treatment. Results shown for all moldboard plow replicate monoliths were similar.

Flow-weighted NO₃-N concentrations of drainage water collected from the ridge tillage treatment peaked at about 102 mg L⁻¹ similar to the moldboard plow treatment, but after 120 mm of drainage had been recorded (fig. 7c). The two curves seemed to depict slightly greater concentrations over a larger range of drainage depths than the chisel plow or moldboard plow treatments. In addition, the minimum concentration reported was greater than 30 mg L⁻¹ compared to 15 to 20 mg L⁻¹ for the chisel plow and moldboard plow treatments. This suggests that if drainage continued to occur, a greater mass of NO₃-N would be leached from the ridge tillage plots.

Tracer concentrations for the BROAD (Cl) (fig. 8) and WATER (I) (fig. 10) application methods typically peaked at less than 100 mg L⁻¹ while the SLOT (Br) treatment (fig. 9) peaked at 100 mg L⁻¹ or more. Peaks of near 250 mg L⁻¹ were recorded for MPR2 and MPR3 (fig. 9b and 9c). After more than 300 mm of drainage, flow-weighted concentrations for the SLOT (Br) treatment did not appear to be approaching a minimum value. Bromide concentrations remained above 70 mg L⁻¹ in all monoliths for the SLOT (Br) treatments (fig. 9) suggesting that additional water would leach substantial amounts of tracer from the root zone. Research by Baker et al. (1997) and Ressler et al. (1997) attempted to develop methods to direct drainage water around the point of nitrogen injection to limit leaching losses. These data tend to support their contention that, if the water is allowed to flow through concentrated application zone, NO₃-N leaching losses could be greater than when the same amount of tracer is applied broadcast.

Results for the BROAD(Cl) and WATER (I) treatment showed peak concentrations of less than 110 mg L⁻¹ and appeared to be approaching a minimum concentration of 30 mg L⁻¹ or less after several hundred millimeters of drainage (figs. 8 and 10). Applying broadcast treatments and, in particular, broadcast applications with an irrigation system resulted in the lowest flow-weighted concentrations, and thus lower tracer leaching loss per millimeter of drainage.

Results for the ridge tillage treatment (fig. 8c, 9c, and 10c) show less variation and lower peak concentrations with the exception of the BROAD (Cl) application method of the chisel plow tillage treatment (fig. 8a). Data for the chisel plow and moldboard plow treatments have similar peak concentrations, but variation among monoliths is greater than for the ridge tillage treatment. This is supported by the data for the range in concentrations recorded for each monolith (table 4). Graphs show that the ridge tillage flow-weighted concentrations track each other for each application method while the other tillage treatments are highly variable. This could result from the surface disturbance caused by the chisel plow and moldboard plow implements which would slice through preferential flow pathways making them less continuous.

Many of the graphs show a dual peak in the flow-weighted concentration curves. The first peak occurred shortly after the first flush for the second water application

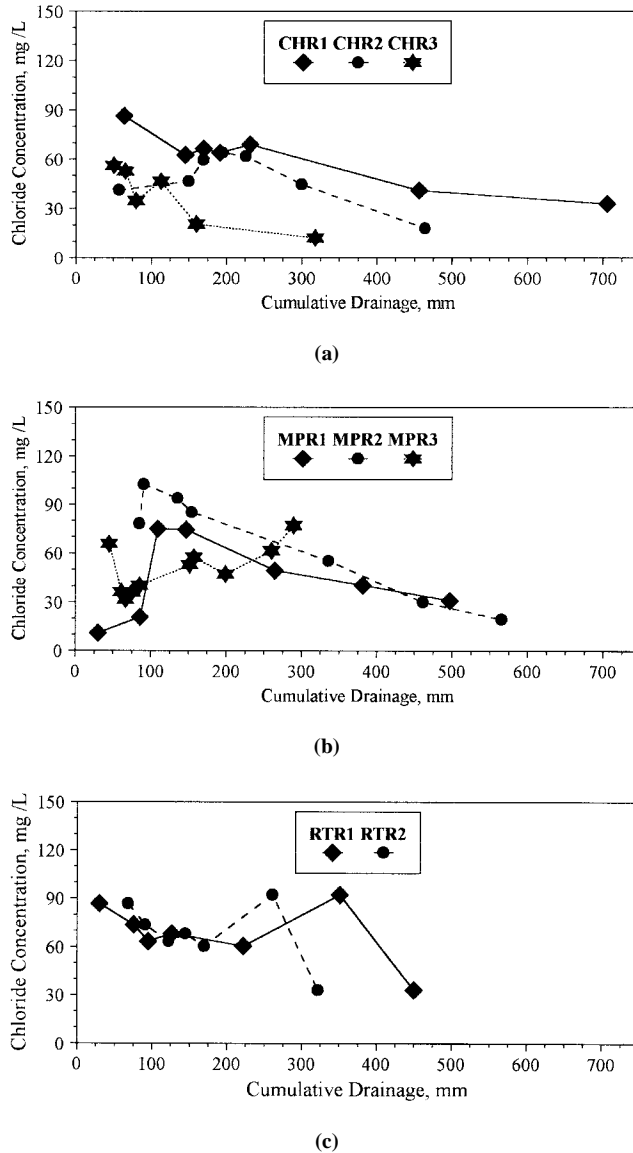
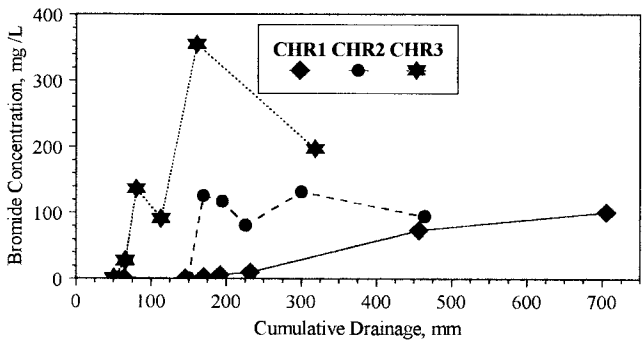


Figure 8—Trends in chloride concentration for drainage resulting from approximately 530 mm of water application for the chisel plow (a), moldboard plow (b), and ridge tillage (c) treatments.

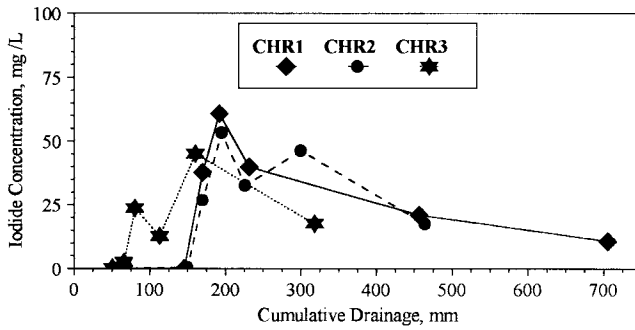
event which would suggest that different amounts of tracer had been moved to the bottom, but not through the monolith during the first water application. The second peak occurred after about 200 to 350 mm of drainage. This was apparently caused by additional tracer that was dissolved in the soil water near the soil surface between water applications. Once dissolved, the addition of more rainfall flushed the tracer through the soil profile and into the leachate collector unit.

SUMMARY

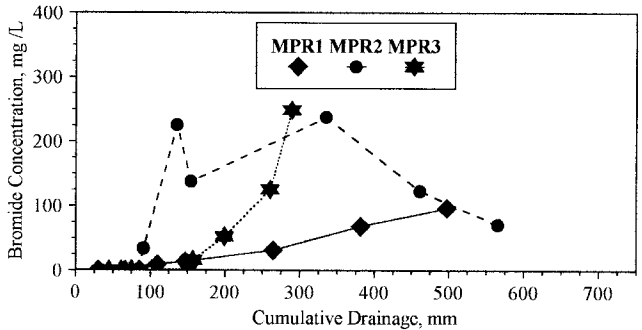
Cumulative distribution curves indicated that some preferential flow pathways existed in each monolith. In all cases, the cumulative distribution curves were above the 1:1 line, indicating that drainage from some cells was substantially greater than others. However, no significant differences were noted for cumulative drainage distribution curves or for the depth of drainage produced ($p < 0.05$).



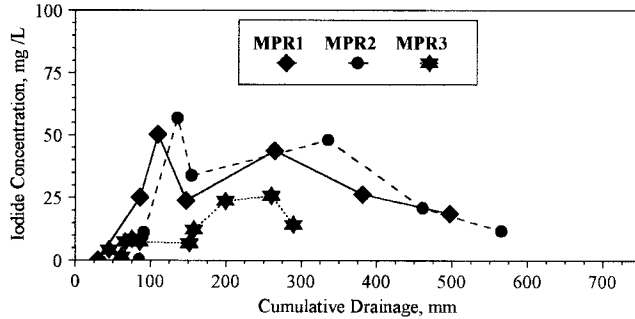
(a)



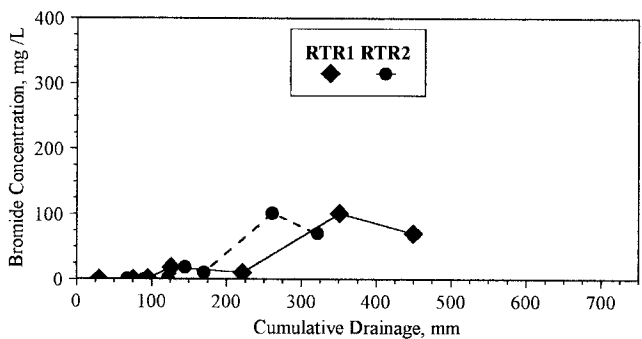
(a)



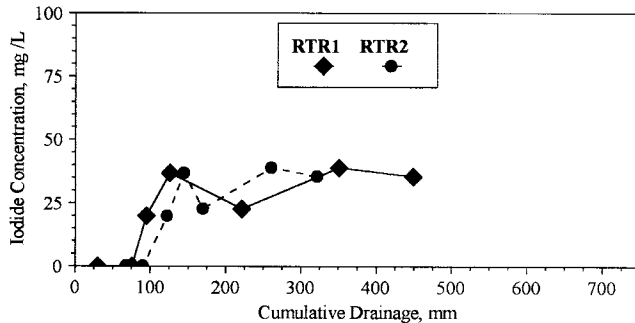
(b)



(b)



(c)



(c)

Figure 9—Trends in bromide tracer concentration for drainage resulting from approximately 530 mm of water application for the chisel plow (a), moldboard plow (b), and ridge tillage (c) treatments.

Spatial analysis indicated that drainage was randomly distributed across the monolith. The SLOT (Br) treatment had little impact on drainage below the application zone, suggesting that the level of compaction may have been insufficient to divert water around the tracer application zone.

No significant differences in nitrate leaching loss were recorded among tillage treatments. However, some trends emerged. The moldboard plow treatment produced the highest CV for nitrate leaching losses and the ridge tillage and chisel plow treatments being nearly equal. Nitrate-nitrogen concentrations peaked at over 100 mg L⁻¹ after 100 to 170 mm of drainage for all tillage practices with the chisel plow treatment recording the greatest leaching loss. These data also indicate the depth of drainage required to transport soil applied tracers to the bottom of the root zone.

Figure 10—Trends in iodine concentration for drainage resulting from approximately 530 mm of water application for the chisel plow (a), moldboard plow (b), and ridge tillage (c) treatments.

Nitrate-nitrogen concentrations for the ridge tillage treatment remained above 30 mg L⁻¹ after 300 mm of drainage were recorded. Thus, it appears that more drainage is required to transport NO₃-N to the bottom of the root zone.

No significant differences in leaching losses were found among tillage treatments or tracer application methods for either water application event ($p < 0.05$). Spatial analysis indicated that leaching losses were randomly distributed across the monoliths. However, results for the SLOT (Br) treatment suggest that if water does move through the application zone due to a water application immediately after application, substantial amounts of tracer would be leached from the soil profile due to subsequent applications. Though not conclusive, significant differences in leaching loss were noted when comparing loss for columns C and D with other columns in three of eight monoliths. Tracer patterns for the BROAD (Cl) and

WATER (I) application methods appeared to be based on drainage collection patterns for each water application. Greater amounts of tracer would be flushed from the SLOT (Br) treatment with additional water applications based on results for the 430 mm water application.

Flow-weighted tracer concentrations showed that the ridge tillage treatment tracked closely between monoliths regardless of the tracer application method, while the chisel plow and moldboard plow produced highly variable results. This is presumably due to reduced soil surface disturbance for the ridge tillage treatment that would allow more continuity of flow paths than in areas tilled with a moldboard plow or chisel plow. Results tend to support an assertion that the moldboard plow tillage treatment combined with the SLOT N application method should be avoided and ridge tillage combined with application of N with irrigation water would produce the least $\text{NO}_3\text{-N}$ leaching.

ACKNOWLEDGMENT. The authors acknowledge the support of the Agricultural and Biosystems Engineering Department of Iowa State University, and the University of Nebraska Agricultural Research Division, the Nebraska Water Center, the Biological Systems Engineering Department and the Northeast Research and Extension Center of the University of Nebraska. Mention of trade names or commercial products is made for illustration only and does not constitute their endorsement by the authors, Iowa State University, nor the University of Nebraska.

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