Nitrate-N and Water Movement in Soil Columns as Influenced by Tillage and Corn Residues

V. K. Serem, C. A. Madramootoo, G. T. Dodds, P. Dutilleul, G. Mehuys

Abstract. *Laboratory soil columns, 0.3 m diameter × 0.7 m long, were used to study nitrate-nitrogen (NO_3^--N) leaching in sandy loam soil cropped to grain corn (*Zea mays *L.). Three tillage practices, no till (NT), reduced tillage (RT), and conventional tillage (CT), with residue (R) and without residue (NR), were studied. In Experiment I, 30 min, 23.6 mm simulated rainfalls were applied at 0, 4, 60, 140 and 180 h. Before the 4 h simulated rainfall, granular calcium ammonium nitrate fertilizer was applied to the soil surface at a rate of 180 kg-N/ha. In Experiment II, using the same columns ten months later, 30 min, 32.3 mm of simulated rainfall were applied at 6, 170, 312 and 412 h, after an initial soaking of the soil (0 h). Fertilizer was applied after 125 h, at the same rate as in Experiment I, but in 1 L (14.4 mm) of solution. NO_3^--N leaching and moisture content were measured at 0.1, 0.2, 0.4, and 0.6 m depths. Drainage water flow only occurred in Experiment II.*

In Experiment I, higher nitrate-nitrogen concentrations ([NO_3^--N]), occurred initially at 0.1 and 0.2 m depths in RT and CT, but less leached to lower soil depths. In the end, more NO_3^--N leached to 0.6 m depth in the NT treatment. In Experiment II, NO_3^--N leached to deeper layers (below 0.4 m) in RD and CT treatments. Conventional tillage exhibited the lowest drainage rates. Tillage and residue effects were statistically significant at the early stages of Experiment I (at 4 h and earlier), and at the later stages in Experiment II, at the 0.1 m depth ($P < 0.05$). Maximum soil NO_3^--N concentration occurred at 0.4 m depth in all treatments. ***Keywords.** Tillage, Nitrate, Water quality, Groundwater, Corn production, Crop residue, Leaching, Fertilizer.*

There are over 6000 corn (*Zea mays* L.) producers on approximately 300 000 ha in Québec. In many large basins, like that of the Yamaska, Richelieu, l'Assomption and Chateaugay rivers, 30 to 40% of agricultural land is devoted to corn. Grain corn growers use in excess of 120 kg/ha/yr of nitrogen fertilizer (Asselin and Madramootoo, 1992). According to AFEQ (1990), the use of inorganic nitrogen fertilizers increased by 40% between 1984 to 1990 in Québec, while acreage remained relatively constant.

Nitrate is the most ubiquitous pollutant in the world's aquifers, and levels continue to increase (Spalding and Exner, 1993). Duttweiler and Nicholson (1983) estimated that in the US, agricultural runoff contributed over 4.6 million Mg of N to off-farm aquatic ecosystems. In the US, about 25% of the 12 million lakes are impaired or partially impaired, and 20% are threatened by nutrients and sediments (USEPA, 1989). About 75% of these are derived from non-point sources. Nutrients and sediments from agricultural sources account for 58% of impaired lakes hectares, 55% of impaired stream hectares, and 21% of estuarine hectares (Wells, 1992). Thus it is not surprising that in Québec, as in the US, nitrate levels well above the safe drinking water limit of 10 mg NO_3—N/L have been detected (Laperriere, 1991).

Drury et al. (1993) showed that over 80% of nitrate losses from monocropped corn grown under conventional, reduced or no-till occurred by leaching to subsurface drains. Nitrogen leaching in the soil, occurs primarily in the form of highly soluble nitrate, is influenced by tillage practices (Boddy and Baker, 1990) and chemical placement methods (Hamlett et al., 1990).

Over the last few years farmers have recognized the advantages of reduced (conservation) tillage in decreasing soil erosion and energy costs. Consequently the use of reduced tillage and no-till practices has increased. Reduced tillage practices usually leave significant amounts of crop residues on the soil surface (at least 30% coverage by area), which reduce runoff and enhance infiltration. Nitrogen losses through surface runoff were reported to be significantly lowered by reduced tillage (Gilliam and Hoyt, 1987). Baker (1987) and Dick et al. (1986) noted that conservation tilled soils showed reduced surface runoff and greater infiltration, and thus potentially higher chemical leaching.

Thomas et al. (1973) and Tyler and Thomas (1979) on silt loam previously cropped to bluegrass, found greater NO_3^--N leaching from broadcast ammonium nitrate under no-till conditions than under conventional tillage. While Tan et al. (1993) found no difference in nitrate losses to tile drains between conventional and reduced tillage, Drury et al. (1993) found no differences in nitrate leaching between reduced and no-till plots, but did show much higher nitrate losses with conventional tillage. Similarly,

Article was submitted for publication in June 1996; reviewed and approved for publication by the Soil & Water Div. of ASAE in April 1997.

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Kanwar et al. (1985) applied water to a loam soil containing largely incorporated nitrogen fertilizer and reported less leaching of NO_3^--N in no-till plots than in conventional tillage plots. Masse et al. (1991) near Ottawa, Ontario, on loam and clay loam soils under continuous corn cropping and fertilized with injected ammonia, also found greater NO_3^--N losses under conventional compared to no-till. Patni et al. (1993) and Tyler and Thomas (1977) both noted that tillage treatment effects could vary substantially from year to year. For example, Kanwar et al. (1993) only found reduced nitrate losses with no-till *versus* conventional tillage in the third year that treatments were applied. One factor that is thought to influence leaching of nitrate in no-till soils is the formation and greater continuity of large channels such as earthworm burrows, root channels, cracks, etc., which are disrupted yearly under conventional tillage (Lodgson et al., 1990). Under some circumstances, these macropores can permit rapid downwards movement of water, bypassing much of the soil matrix (Kanwar et al., 1990). Gilliam and Hoyt (1987) suggested that such preferential water flow might increase leaching of surface applied fertilizer-N (e.g., Thomas et al., 1973; Tyler and Thomas, 1979), but largely bypass nitrate already in the soil (e.g., Kanwar et al., 1985; Masse et al., 1991; Drury et al., 1993). Thus, such flow would be highly dependent on timing, route and volume of incoming water (Milburn et al., 1990).

Consequently, tillage practices and chemical application methods are important factors in the control of leaching losses and reduction of amounts of agricultural N reaching surface waters via groundwater discharge. The success of field studies on effects of tillage and crop residues on chemical leaching is hindered by variability in soil properties and the inability to control environmental factors. Soil columns have been used to eliminate or reduce these difficulties, as well as study processes, develop strategies, and evaluate impacts related to the fate of nitrates in the soil (Coltman et al., 1991; Cassel et al., 1984), atrazine (Smith et al., 1989), and urea (Priebe and Blackmer, 1989). The concentrations of these chemicals in the soil depend on the frequency and amount of water applied. In order to observe this temporal behavior, the processes should be monitored for several water applications over time.

Therefore, the purpose of this study was to investigate the effects of three tillage practices and corn residue on water and nitrate movement in soil columns, for different time durations and soil depths.

Materials and Methods

Field Site

The soil columns were taken from McGill University, Macdonald Campus research farm in Ste. Anne-de-Bellevue, Québec. Shallow St. Amable sandy loam and significant areas of Courval sandy loam or loamy sand (Typic Endoaquent) make up most of the site. These are underlain, at an average depth of 0.46 m, by a Ste. Rosalie grey marine clay.

In 1987 through 1989, the 2.4 ha site was planted to grain corn. In 1990, the site was planted to haylage: 60% alfalfa (*Medicago sativa* L.), 30% bromegrass (*Bromus inermis* L.), and 10% orchardgrass (*Dactylis glomerata* L.), cut in September 1990, and an oat-wheat-barley mix, cut in July 1990 (Burgess et al., 1996). In 1991, the site was again planted to grain corn (Funk 4120 hybrid).

In the fall of 1991, grain was harvested with a two-row New Holland 890 forage harvester with either a two-row silage head which left only stubble on the field (0.8 Mg residue/ha) or a high-moisture corn head which did leave behind the residue (9 Mg residue/ha). A 0.04 ha parcel, with a minimum depth of sandy loam soil of 0.7 m, and portions with (R) and without residue (NR) was chosen. Each portion of the parcel then received one of three tillage treatments: (1) No till (NT), not cultivated at any time; (2) reduced tillage (RT), tandem-disced 10 to 15 cm deep (2-3 passes) in fall 1991 and again in spring 1992 (2 passes); and (3) conventional tillage (CT), moldboard ploughed 20 cm deep in fall 1991 and disced as for RT in spring 1992, creating 18 different sub-parcels. In the spring of 1992, soil residue cover in adjoining field plots having received identical tillage and residue practices were: CTNR (< 1%), RTNR (< 5%), and CTR and NTNR (< 9%) plots (Burgess et al., 1996).

In June 1992, for each sub-parcel, one set of eight, 0.1-m deep × 0.1-m diameter soil cores, down to a depth of 0.8 m, were obtained. Bulk densities and saturated hydraulic conductivities for each layer of each treatment were measured by the falling head method (Klute and Dirksen, 1986), and ranged from 1050 to 1690 kg/m^3, and

Table 1. Values for soil bulk density (ρ, kg/m^3) and saturated hydraulic conductivity (K_{sat}, m/day) for the soil used in the experiment

		Treatment*				
Depth (m)		NT	RTR	RTNR	CTR	CTNR
0-0.1	ρ	1260	1390	1050	1220	1190
	K_{sat}	2.46	9.81	9.84	2.82	4.21
	stderr†	0.010	0.150	0.150	0.010	0.179
0.1-0.2	ρ	1150	1250	1250	1220	1280
	K_{sat}	4.81	1.86	2.62	1.36	4.10
	Stderr	0.115	0.025	0.080	0.035	1.095
0.2-0.3	ρ	1340	1370	1260	1180	1150
	K_{sat}	4.59	3.10	3.12	4.23	0.48
	Stderr	0.105	0.005	0.005	1.13	0.015
0.3-0.4	ρ	n/a	1420	1520	1320	1230
	K_{sat}	n/a	2.19	2.20	0.51	0.50
	Stderr	n/a	0.005	0.005	0.010	0.010
0.4-0.5	ρ	1310	1500	1690	1250	1280
	K_{sat}	3.75	0.55	0.54	0.56	0.73
	Stderr	0.055	0.005	0.005	0.010	0.000
0.5-0.6	ρ	1570	n/a	1350	1330	1330
	K_{sat}	2.30	n/a	1.39	0.05	1.39
	Stderr	0.010	n/a	0.020	0.000	0.015
0.6-0.7	ρ	1550	1490	1610	1400	1410
	K_{sat}	1.35	2.26	2.24	0.05	1.39
	Stderr	0.130	0.06	0.060	0.000	0.000

* NT, RT, CT = No-till, Reduced tillage, and Conventional tillage, respectively. R, NR = Residue and No residue, respectively. Data for NT are the same for R and NR since residue was applied on surface and hence does not affect the soil density; sample was taken before residue was applied.

† Standard error for K_{sat}, based on two sets of readings from the falling head experiment. n/a not available (samples damaged).

0.05 to 9.84 m/day, respectively (table 1). These parameters were not measured in the columns themselves.

Collection and Handling of Columns

PVC pipes (SDR 35 sewer type), 1 m long × 0.3 m outside diameter and 10 mm wall thickness, tapered to 2 mm at the bottom end, were pushed into the soil by the bucket of a backhoe. Waterproof grease was applied on the inside walls of these pipes before being driven into the soil to reduce possible water bypass along the sides. Six columns were obtained from the NT -R subparcel, three of which were used as is (NT -R) and three of which had 7 Mg/ha of residue applied to the top of the column (NT +R) before experimentation began. An additional 3 columns from the CT –R, CT +R, RT –R and RT +R subparcels, resulted in a total of 18 columns, representing 3 replicates of each tillage × residue treatment.

Treatments and Instrumentation

After carefully transporting the soil columns in an upright position to the laboratory, excess soil was removed from the bottom of each column to a final depth of 0.7 m. The columns were then sealed tightly at the bottom by fusing a 6-mm thick circular PVC plate into the pipe wall using a commercial PVC solvent and a silicon sealant. A needle-punched non-woven geotextile (density 0.2 kg/m^2, opening size 38 μ was placed at the interface between the soil and the bottom plate. A Y-shaped glass tube connector, 7-mm inside diameter, was placed at the center of the plate to drain the leachate, as shown in figure 1(a). The soil columns were then mounted onto a platform, 0.3 m above the floor.

A set of three horizontal 6-mm diameter stainless steel rods, spaced 50 mm apart, were inserted 155 mm into each column, at 0.1, 0.2, 0.4, and 0.6 m depths, for measurement of moisture content by time-domain reflectometry (TDR: Tektronix model 1502B metallic cable tester) developed and described by Topp and Davis (1985). Three rods were chosen, rather than two, because they emulate coaxial transmission lines and reduce spurious noise and reflections, thus giving clearer signals and more accurate water content measurements.

At each depth, 7-mm I.D. glass tubes, fitted with 100 kPa ceramic tips at one end, were placed horizontally 150 mm into the soil column (fig. 1a). With the aid of 100 kPa hand suction pumps, water samples were collected from the tubes. Nitrate-N concentrations were determined by a Technicon autoanalyser (Model 1, Technicon Instruments Corporation, Chauncey, N.Y.).

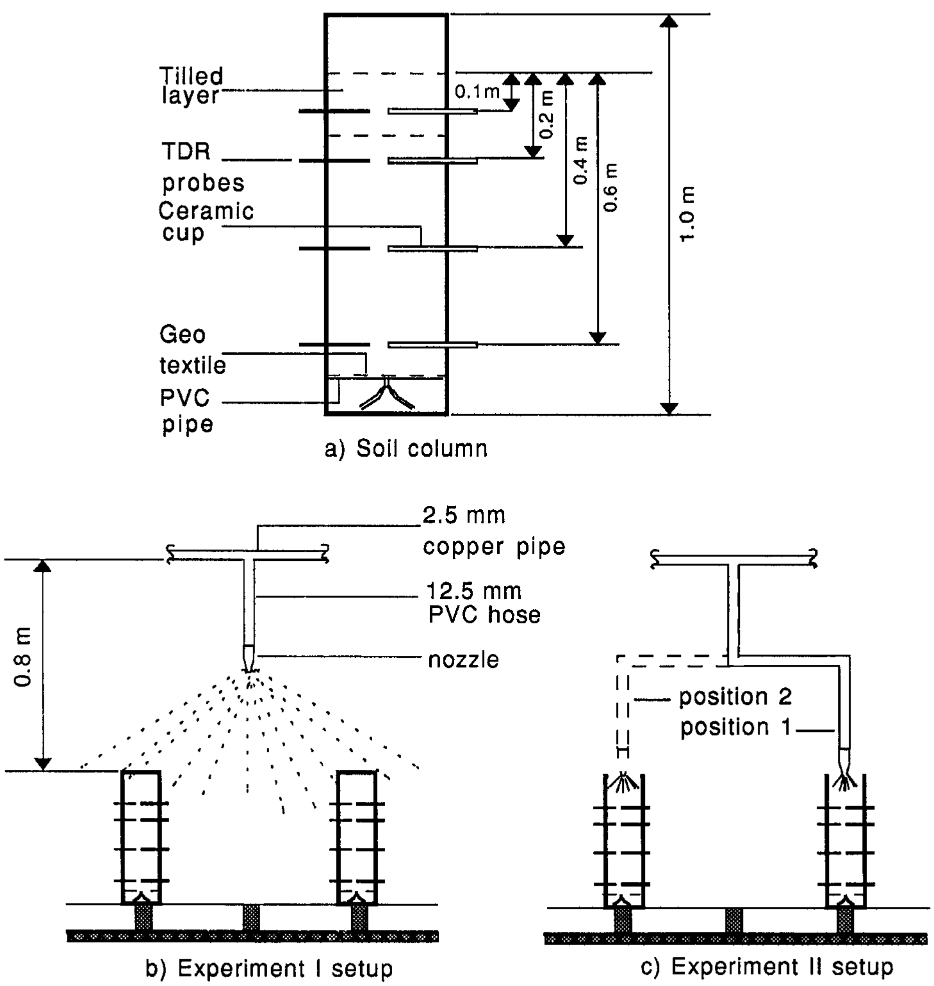

Figure 1–Schematic of soil column and water applications in experiments I and II.

Experimental Design

Experiment I was conducted in August to September 1992. Based on statistical analysis of long-term local weather data, the once-in-five-year, 30-min duration storm for this location was 50 mm/h. To obtain the total of about 100 mm of simulated rainfall (30-year local mean August precipitation) after fertilizer application at 4 h, an average of 23.6 ± 1.9 mm water (table 2) was applied over 30 min at 4, 60, 140, and 180 h. These times were chosen as best allowing the management of data collection. Fertilizer, 4.5 g (1.25 g-N: equivalent to 180 kg-N/ha) of calcium ammonium nitrate fertilizer (27-0-0), was applied in granular form to each soil column, prior to the 4 h watering (fig. 2). The same 23.6 mm of simulated rainfall was applied initially (0 h) in order to moisten the soil and allow for sampling of initial nitrate levels.

Rainfall was simulated by a full cone spray nozzle (Unijet model 1/4 TG, Spraying Systems Co., Wheaton, Ill.) with a capacity of 0.215 L/min when operating at a pressure of 140 kPa and spray angle of 56°. The nozzles were placed 0.8 m above the soil columns. Each nozzle supplied water simultaneously to two adjacent soil columns (fig. 1b) placed within the diameter of coverage. The actual capacity for each nozzle was determined by measuring the volume of water discharged in 2 min by each nozzle operating at a pressure of 200 kPa (table 2).

Table 2. Nozzle discharge capacities and actual amounts of water received by each soil column from nozzles placed 0.8 m above the columns, operating at 200 kPa pressure

			Water Applied					
			Experiment I			Experiment II		
Noz-zle	Nozzle Dis. (L/h)	Col.	(L/h)	(mm/ 1/2 h)*	Total†	(L/h)	(mm/ 1/2 h)‡	Total†
1	18.4	1	3.4	24.7	98.8	4.4	31.9	110.1
		4	3.5	25.4	101.6	4.5	32.9	113.1
2	17.1	2	3.3	24.0	96.0	4.5	32.6	112.2
		5	3.2	23.0	92.0	4.6	33.0	113.4
3	15.2	3	4.0	28.7	114.8	4.6	32.9	113.1
		6	3.1	22.5	90.0	4.6	32.9	113.1
4	16.9	7	---	---	---	---	---	---
		10	3.3	23.8	95.2	4.5	32.1	110.7
5	16.5	8	2.7	20.3	81.2	4.7	33.7	115.5
		11	3.3	23.6	94.4	4.5	32.7	112.5
6	17.6	9	3.2	23.3	92.8	4.5	32.7	112.5
		12	3.3	23.4	93.6	4.5	32.4	111.6
7	17.6	13	3.2	23.0	92.0	4.5	32.7	112.5
		16	3.1	22.6	90.4	4.5	32.4	111.6
8	16.9	14	3.5	25.0	100.0	4.6	33.2	114.0
		17	3.0	21.4	85.6	4.5	32.3	111.3
9	17.0	15	3.5	24.9	99.6	4.6	33.2	114.0
		18	3.1	22.5	90.0	4.5	32.5	111.9
Mean				23.6			32.3	
Standard deviation				1.9			1.6	

* Amounts applied at each of five water applications in experiment I.
† Total water applied (mm) after fertilizer application (four applications).
‡ Amounts applied at each water application in experiment II, except at time of fertilizer application when 14.4 mm water was applied.

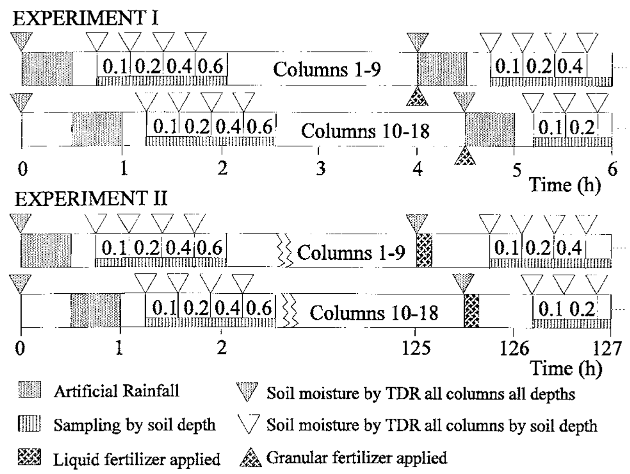

Figure 2–Schematic of methods for experiments I and II.

Water Sampling and Moisture Content Measurements

Water was applied to each column for 30 min (fig. 2). Water sampling and TDR measurements commenced 45 min after starting each water application. To determine the moisture movement in each treatment as influenced by each simulated rain, TDR measurements were taken before each simulated rainfall, and at the time of the subsequent water sampling. The experiment was done with two, 30-min staggered sets of 9 columns (fig. 2). Water sampling and TDR measurements at the same depths in all columns were completed before proceeding to the next depth. Between depths the same order of sampling was maintained from column to column. Although water sampling and TDR measurements lasted for as long as 2 h, this duration was found difficult to display on the same scale for all graphs. Therefore, the moisture and nitrate-N data shown are for 45 min to 2 h after the indicated time in both experiments I and II. These graphs were plotted from the mean values computed across the three replicates of each treatment. No trends attributable to the delays in sampling were detected in the data.

In experiment I, no freely draining water was collected from the bottom of the columns, because the soil remained generally unsaturated throughout the experiment. Since the soil columns were not covered, evaporation could freely occur from the soil surface.

Experiment II: Fertilizer Applied in Solution

Experiment II was carried out in July 1993, using the same columns as used in Experiment I. However, unlike Experiment I where each nozzle supplied simulated rainfall to two columns, the nozzles were modified so that each nozzle supplied rainfall to one column for 30 min, after which the nozzle was directed to the adjacent column for the next 30 min (fig. 1c). Again two sets of nine columns were run at a 30 min interval (fig. 2). The average amount of simulated rainfall applied was 32.3 ± 1.6 mm/application (table 1). The higher amounts in experiment II are a result of the rearrangement of the nozzles (fig. 1c).

Before fertilizer application, water was applied at time 0 (fig. 2), and 6 h later, to make the soil wet before fertilizer application. At 125 h, 1 L (equivalent to 14.4 mm) of a

0.45% (w/w) solution of the fertilizer used in Experiment 1 was applied, over a 10 min period, to each column, using watering cans. No simulated rainfall was applied at 125 h (fig. 2) Simulated rainfall was again applied at 170, 312, and 480 h. Water sampling started 45 min after the cessation of fertilizer application, and subsequent water samples were taken 45 min after starting each simulated rainfall.

Drainage Water Sampling

In addition to sampling water from 0.1, 0.2, 0.4, and 0.6 m depths, freely draining water was sampled from the bottom of the columns and used to determine [NO_3^--N] in the drainage water. No drainage occurred before or at time of fertilizer application. The first drainage was sampled at 170 h, and subsequently at 312 and 480 h. These three sampling time points were designated Rain2, Rain3, and Rain4, according to the sequence of water applications after fertilizer placement. The time to drain a measured volume of water was also taken intermittently until the flow ceased. Besides these changes, other sampling procedures remained exactly as in experiment I.

Statistics

The experimental design was a two-way factorial design (Sokal and Rohlf, 1995), with spatio-temporal repeated measures. The two treatment factors that were crossed consisted of three tillage practices, no-till (NT), reduced (RT), and conventional (CT), and two rates of residue, 7 Mg/ha (R) and no residue (NR). There were four levels for the spatial repetition factor, depth, and five levels for the temporal repetition factor, time duration after water application.

The univariate approach to the analysis of variance (ANOVA) of repeated measures was modified due to the heteroscedasticity (inequality of variances) and autocorrelation (lack of independence) of the data, by application of a correction factor to the number of degrees of freedom of the F-statistics involving either of the repetition factors, time, and depth. The relevant methodology is presented by Crowder and Hand (1990); the spatio-temporal case is treated in Dutilleul (1996). This correction factor, called epsilon (ε), can be estimated following Greenhouse and Geisser (1959), and its theoretical value ranges from $1/(p - 1)$ to 1.0, where p is the number of repeated measures (p = 4, 5, or 20 for temporal, spatial, or spatio-temporal, respectively). Its effect is to reduce the number of degrees of freedom according to the size and magnitude of heteroscedasticity and autocorrelation.

The repeated measures analysis of variance was performed using the GLM procedure of SAS Version 6, option REPEATED, and the levels of the two repetition factors were arranged as required (SAS Institute Inc., 1989).

Results and Discussion

Experiment I: Fertilizer Applied in Granular Form

Nitrate-N Leaching. Figure 3 shows the variations in nitrate-nitrogen concentration ([NO_3^--N]) in μg/L of soil-extracted water for NT, RT, and CT, over nine days of experiment I. The [NO_3^--N] in the NT treatment increased in the 0.1 m depth during the first 60 h, while [NO_3^--N] in the CT and RT treatments reached their peak and started dropping in less than 60 h. The immediate leaching of NO_3^--N in the 0.1 m soil layer in the CT and RT treatments suggests that the applied water redistributes the dissolved fertilizer within the ploughed layer. Such a delay in the movement of fertilizer in solution the lower depths might be attributable to the presence of a plough pan, but this was not specifically investigated. After fertilizer application, for the NT-R treatment there was an immediate increase of [NO_3^--N] in the 0.6 m soil layer, which remained the highest until the end of the nine days in the NT treatment. This would suggest that little NO_3^--N moved to lower layers.

Spatio-temporal Repeated Measures ANOVA. There was no significant tillage-residue interaction during the experiment, whatever the depth and time duration after water application (table 3). Residue main effects were significant initially (0 h) at 0.1 m and 0.4 m depths ($P < 0.05$). At 4 h (when fertilizer was applied), residue main effects were highly significant ($P < 0.01$) at 0.4 m depth. Tillage main effects were significant ($P < 0.05$) at 0.1 and 0.4 m initially, at 0.1 and 0.2 m at 4 h, and at 0.2 m depth at 60 h. This trend would suggest that tillage effects become more significant with time at deeper soil layers. However, after 60 h, there were no significant effects of tillage or residue.

The adjusted probabilities of significance for the observed F-values (table 4) indicate that the depth-residue interaction is the only factor that tends to significance ($P < 0.1$). This can be attributed to the variations in the initial [NO_3^--N], which were found to be highest in the lower depths of the soil profile. That effect was further examined by using polynomial contrasts for depth. The only significant ($P < 0.05$) contrast found was the quadratic depth contrast for residue, suggesting that the two rates of residue differed in the quadratic component of the NO_3^--N movement along the four soil layers.

The above results have indicated that deeper leaching occurred in the NT practice than in RT and CT treatments. Similar results were observed by Tyler and Thomas (1977). NT plots, unlike RT or CT plots, usually contain some continuous undisturbed pores that allow preferential movement of water. Furthermore, the physical structure of NT surface layer tends toward more stable aggregates, higher porosity and water-holding capacity, and a greater percentage of macropores (Reganold et al., 1990). The soluble calcium nitrate fertilizer, applied to the soil surface, is more likely to be dissolved by the water and to be carried down the soil profile through existing preferential flow channels. Generally, in RT and CT treatments, there are no unbroken macropores leading from the soil surface to the subsoil (Smith et al., 1990). The more uniform water redistribution on the tilled soil layer resulted in higher NO_3^--N as we observed. Deep leaching is of course undesirable as it leads to groundwater pollution and fertilizer losses. The less leaching observed in reduced and conventional tillage practices means higher amounts of nitrate remains in the root zone, thereby being available to crops. Since there are reductions in energy costs associated with RT, this tillage practice is to be preferred over the conventional tillage.

Experiment II: Fertilizer Applied in Solution

Nitrate Leaching. The results for nitrate leaching through the NT, RT, and CT soil columns in experiment II are presented in figure 4. The NO_3^--N movement in both RTR and CTR treatments was rapid and increased with depth, but decreased with time after fertilizer application. This tended to increase [NO_3^--N] in the lower soil layers.

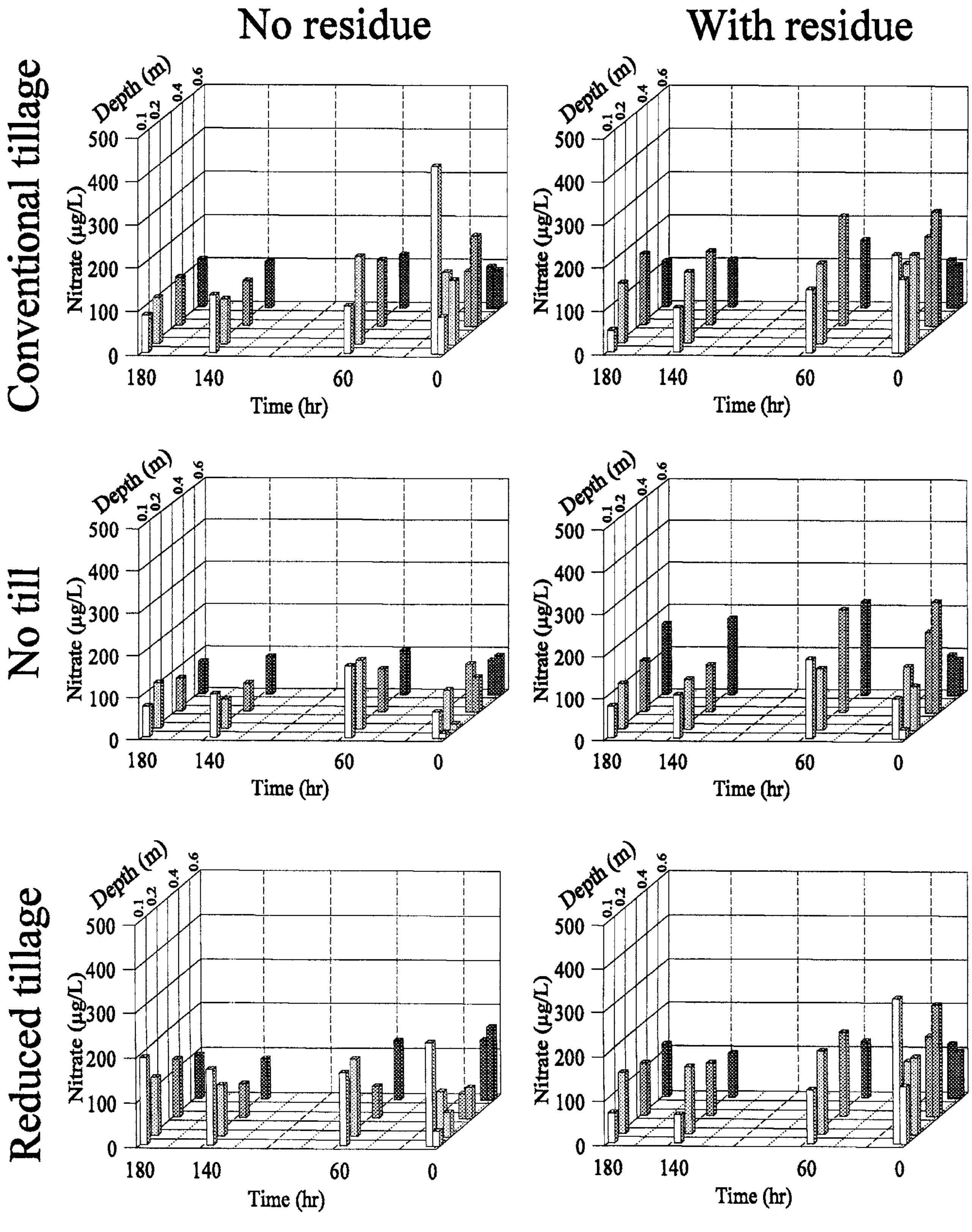

Figure 3–Variation in nitrate-N concentration with time and depth in experiment I.

No-till with residue (NTR) showed rapid and deeper NO_3^--N leaching (to 0.6 m) after fertilizer application, even though initial [NO_3^--N] was similar to that in CTR and less than that in RTR. Residues in NT plots seemed to encourage deeper NO_3^--N leaching and reduce [NO_3^--N] distribution in the upper layers.

In reduced tillage with no residue (RTNR) and conventional tillage with no residue (CTNR) treatments, [NO_3^--N] increased with depth, but decreased with time.

Table 3. Analysis of variance for Nitrate-N concentration in the soil water solution (mg/L), per depth (m) and time (h) after water application

Hours Experiment 1/2	Depth (m)	Pr > F Experiment I Tillage	Experiment I Residue	Experiment I Till × Res	Experiment II Tillage	Experiment II Residue	Experiment II Till × Res
0/6	0.1	0.0784	0.0742	0.3012	0.8484	0.3097	1.000
	0.2	0.3095	0.1490	0.8860	0.4347	0.3844	0.3831
	0.4	0.2749	**0.0096**	0.3887	**0.0215**	0.1079	**0.0047**
	0.6	0.2863	0.4732	0.4709	0.7315	0.9605	0.8736
4/125	0.1	**0.0166**	0.6999	0.1605	0.8484	0.3097	1.000
	0.2	0.2187	*0.0846*	0.7111	0.6504	0.3502	0.3859
	0.4	0.3594	**0.0068**	0.7799	0.8616	0.9042	0.4649
	0.6	0.4020	0.7901	0.8383	0.7004	0.6643	0.4381
60/170	0.1	0.3182	0.8911	0.5194	0.8484	0.3097	1.000
	0.2	0.7922	0.8812	0.9416	0.1274	0.7568	0.6583
	0.4	0.4909	**0.0322**	0.9436	0.8707	0.8219	0.5921
	0.6	0.7831	0.2810	0.5169	0.0938	0.3895	0.3008
140/312	0.1	0.9248	0.1651	0.3669	0.8484	0.3097	1.000
	0.2	0.4621	*0.0695*	0.8798	**0.0030**	0.1002	**0.0420**
	0.4	0.1932	**0.0296**	0.8662	0.4864	0.6806	0.1713
	0.6	0.5818	0.3042	0.4848	0.2107	0.9464	0.1364
180/480	0.1	0.5010	0.3008	0.5208	0.8484	0.3097	1.000
	0.2	0.1635	0.1679	0.3847	**0.0006**	0.1292	**0.0123**
	0.4	0.5197	0.2833	0.5535	0.3476	0.2799	*0.0504*
	0.6	0.7513	*0.0770*	0.1237	0.8190	0.9060	*0.0571*

Not significant ($P \geq 0.10$).
Somewhat significant ($0.05 \leq P < 0.10$).
Highly significant ($P < 0.05$).

NTNR retained higher [NO_3^--N] in the upper 0.2 m soil layers than RTNR and CTNR. This confirms that NO_3^--N leaching is slower in NT treatment, as observed earlier. Overall, however, there was less leaching to lower depths in the NT, contrary to observations of experiment I. The water flow through continuous macropores in NT would easily bypass the fertilizer redistributed in the upper soil layers and thus lead to the less leaching to the deeper layers. For treatments with no residue, [NO_3^--N] increased gradually with depth, while for those with residue, the maximum [NO_3^--N] was observed at 0.4 m depth. Overall, greater amounts of NO_3^- N leached to 0.6 m in the CT columns than in NT and RT columns. These observations are consistent with Kanwar et al. (1985), Angle et al. (1993), and Levanon et al. (1993). These researchers attributed the deeper CT leaching to greater mineralizing activity in the CT soil compared with NT and RT soil. It has also been suggested that lack of large macropores in CT practices cause the infiltrating water to move down the soil profile as a front, carrying the NO_3^--N with it resulting in greater leaching (Smith et al., 1990).

Spatio-temporal Repeated Measures ANOVA. The tillage-residue interaction was significant ($P < 0.05$) for 0.6 m depth at 6, 125, and 170 h, for 0.2 m depth at 6 h, and for 0.1 m and 0.4 m depths at 480 h (table 4). The increase in [NO_3^--N] in the deeper layers of the soil can therefore be attributed, at least partly, to the tillage-residue interaction.

There were no significant residue main effects except at 6 h for 0.6 m depth. Tillage main effects were significant ($P <$ 0.01) only at 0.1 m depth at 312 h and 480 h, and at 0.6 m depth at 480 h. This suggests that tillage did not influence NO_3^-- N movement to lower depths in the early part of the experiment, immediately following fertilizer application.

The depth main effects and depth-residue interaction were the only sources of variation that significantly influenced NO_3^--N movement (table 4). Examination of the relevant depth contrasts, on average (mean) or combined with a treatment factor, shows a significant ($P < 0.05$) linear effect and highly significant ($P < 0.01$) quadratic effect of depth on one hand, and significant differences between tillage levels and residue levels in the quadratic effect of depth. This suggests that (1) a quadratic function, including a linear term, provides a very good description of NO_3^--N movement; and (2) the curvature of the NO_3^--N movement along soil layers is not constant among tillage levels and among residue levels.

Table 4. Repeated measures analysis of variance for nitrate-N concentration in the soil water, with time after water application and depth as repetition factors

Source	df	Experiment I Pr > F	Experiment I Pr > F Adj. [G-G]*	Experiment II Pr > F	Experiment II Pr > F Adj. [G-G]*
Tillage (Till)	2	0.1646	n/a	*0.0575*	n/a
Residue (Res)	1	*0.0657*	n/a	*0.0528*	n/a
Error	2				
Time	4	**0.0064**	*0.0891*	0.6318	0.5568
Time × Till	8	0.1295	0.2868	0.5845	0.5555
Time × Res	4	0.1932	0.2893	0.4648	0.4850
Error (Time)	8				
Depth	3	**0.0335**	0.1257	**0.0059**	*0.0970*
Depth × Till	6	**0.0290**	0.1381	0.2311	0.4021
Depth × Res	3	**0.0034**	*0.0501*	0.2295	0.3552
Error (Depth)	6				
Time × Depth	12	**0.0004**	0.1157	0.1785	0.4141
Time × Depth × Till	24	0.1228	0.3558	0.3933	0.5452
Time × Depth × Res	12	0.1832	0.3344	0.5122	0.5029
Error (Time × Depth)	24				

Polynomial Contrast		Pr>F Experiment I Mean	Experiment I Tillage	Experiment I Residue	Experiment II Mean	Experiment II Tillage	Experiment II Residue
Depth	1	0.2327	0.1019	0.1509	**0.0390**	0.2990	0.2687
	2	0.1049	0.2173	**0.0375**	*0.0846*	*0.0585*	**0.0461**
	3	0.1427	0.3963	0.3547	0.6487	0.6964	0.9355
Time	1	0.1628	0.3768	0.3051	0.1186	0.5590	0.1422
	2	*0.0599*	0.1040	0.6894	0.6490	0.6024	0.9977
	3	**0.0092**	*0.0723*	0.3664	0.7674	0.7589	0.7206
	4	0.1076	0.6653	0.2140	0.7822	0.4177	0.3256

Not significant ($P \geq 0.10$); *Somewhat significant* ($0.05 \leq P < 0.10$); **Highly significant** ($P < 0.05$).

* Greenhouse and Geisser (1959) correction factor to df of the F-statistics involving either of the repetition factors, or both. This factor provides adjusted probabilities of significance and is necessary in most repeated measures ANOVAs due to heteroscedasticity (inequality of variances) and autocorrelation (lack of independence) of the data.

Depth.n or Time.n — nth degree polynomial contrast for depth or time.

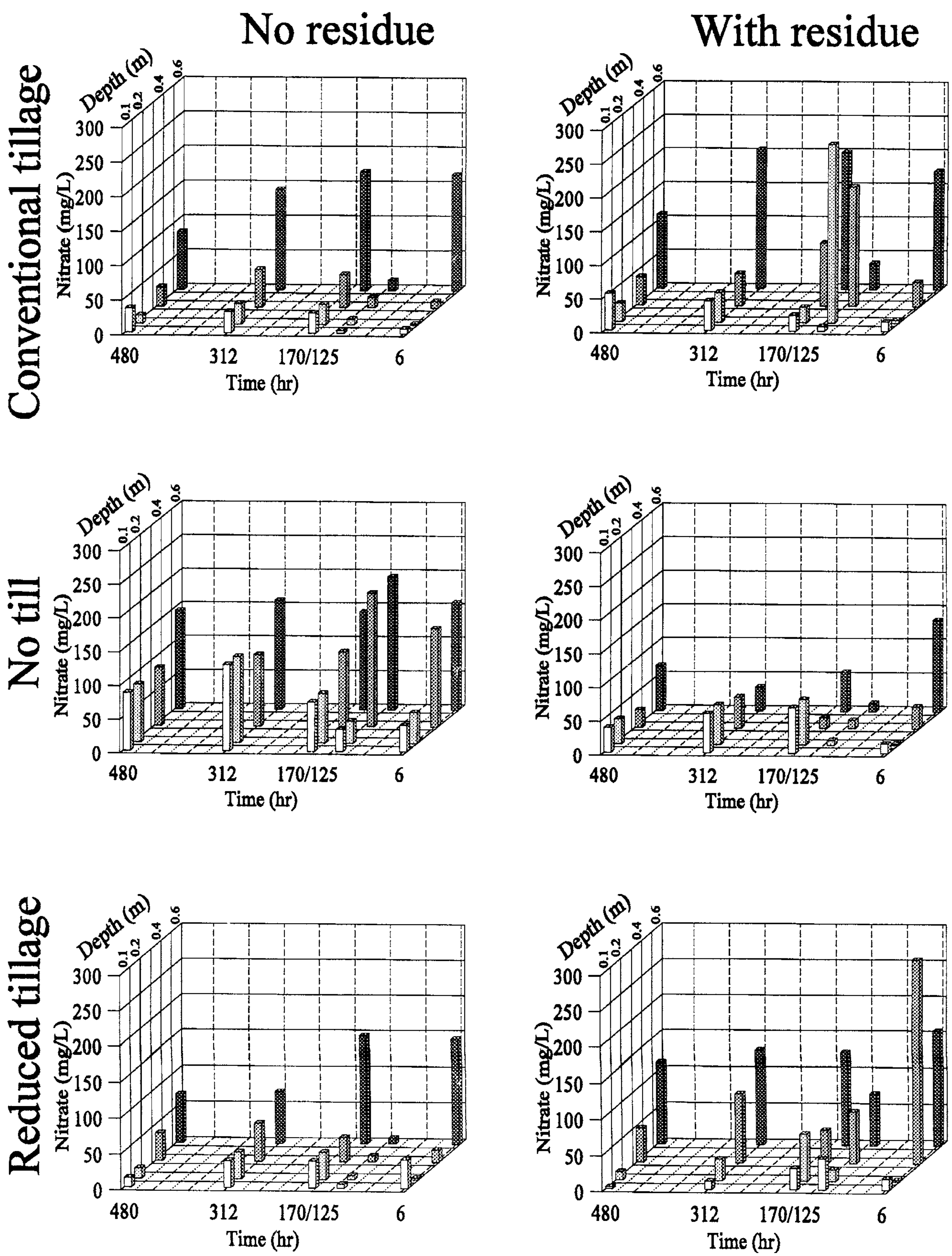

Figure 4–Variation in nitrate-N concentration with time and depth in experiment II.

Moisture Changes Effects on Nitrate-N Leaching

Figures 5 and 6 show water content changes in 0.1 m soil layer following every water application for each of the six treatments in experiments I and II. Graphs for 0.2, 0.4, and 0.6 m soil layers were also plotted, but only charts for 0.1 m layer are included for illustration. Both moisture content data and [NO_3^--N] data shown are the mean of 3 replicates; the moisture content values were so similar across replicates that the deviations are not noticeable in the charts.

Comparison of moisture content changes in time between tillage treatments within the top 0.2 m soil layers in experiment I showed slightly higher moisture changes in the NT and CT treatments than in RT treatment for each water application. One would, therefore, expect NO_3^--N to move more in the NT and CT treatments than in RT within the 0-0.2 m soil layer, if indeed the water movement had a corresponding NO_3^--N movement. However, within the top soil layer, the increase in [NO_3^--N] was greater in the RT and CT treatments than in NT. This suggests that the higher moisture in the NT treatment did not necessarily move down immediately with the fertilizer, indicating that the rate of fertilizer movement was somehow inhibited. At the end of the nine days of experiment, however, there was greater [NO_3^--N] increase in the NT treatment than in CT and RT at the 0.6 m depth. Thus the initial high NO_3^--N movement observed in the CT treatment at 0-0.2 m soil layer did not continue at the same rate to the 0.6 m depth. Furthermore, no significant difference in moisture was observed at the 0.6 m, yet there was a difference in the [NO_3^--N].

In experiment II (fig. 6), while greater overall NO_3^--N leaching occurred in CT and RT treatments, the rate of drainage was lowest in CT treatment. This lower rate of water movement in CT treatment may have been caused by the plough pan layer which inhibits water movement down the soil profile. The increased horizontal movement of water within the tilled layer in CT increases contact time for water with fertilizer, which leads to greater leaching of NO_3^--N. Furthermore, the undisturbed soil in the NT columns contains continuous macropores that usually act as low resistance channels for water flow. Under such conditions, water moves down faster and has less contact time with surface fertilizer. Residues appear to have acted as channels of preferential flow of water, thereby leading to greater flow rates in treatments with residues.

Drainage from Soil Columns

Water Flow. Hydrographs for water flow collected from the bottom of each column, and their corresponding [NO_3^--N] during three water application events, are shown in figures 6, 7, 8. There are no data for Rain0 and Rain2 in the figures, because no drainage occurred before Rain2. In the NT treatments higher flow rate peaks were observed in columns with no residue, depicting higher flow rates. In RT and CT treatments, higher flow rate peaks occurred in columns with residue.

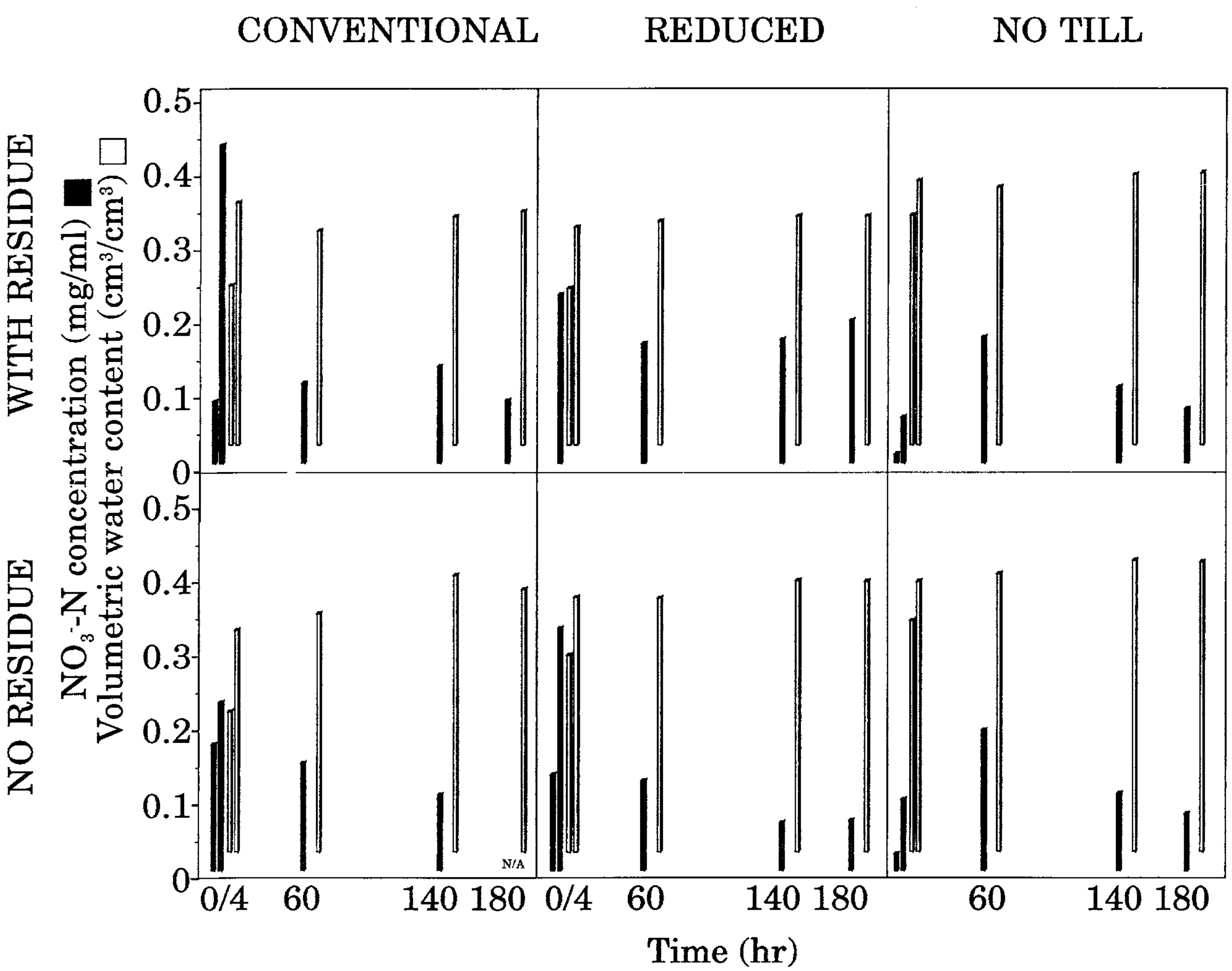

Figure 5–Variation of nitrate-N concentration and water content with time in the 0.1 m soil layer in experiment I.

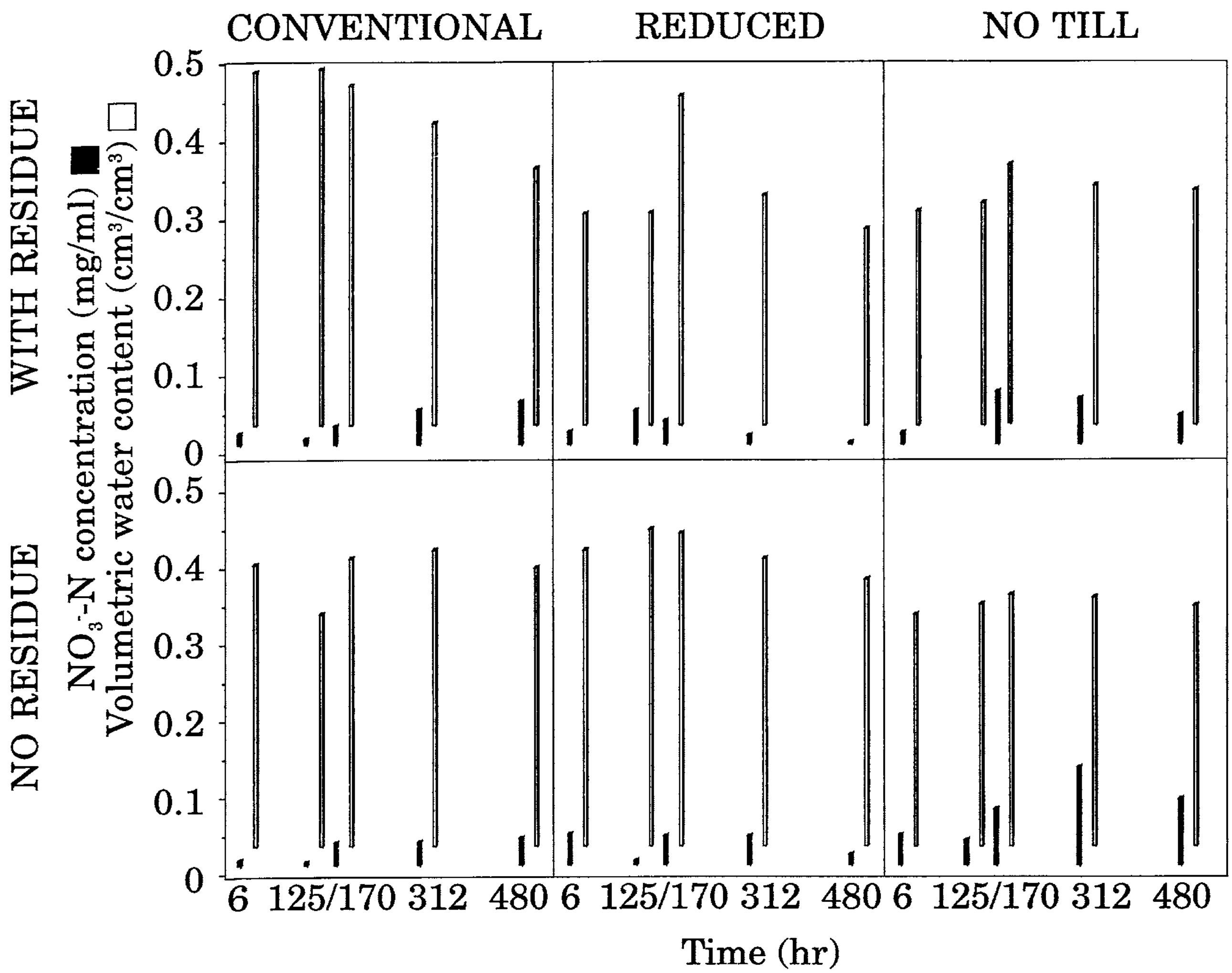

Figure 6–Variation of nitrate-N concentration and water content with time in the 0.1 m soil layer in experiment II

These observations suggest that (1) the placement of residue in RT (partially incorporated) and in CT (fully incorporated) allowed high water flow rates; (2) residue left on the surface in NT columns inhibited water flow. In RT and CT, the residue incorporated in the soil may serve as channels of accelerated water flow as the water makes its way through the soil matrix. In the NT treatment, the water in no-residue columns finds its way directly into existing macropores, but in the columns with residue, the water is redistributed at the surface, thus moving through the soil matrix rather than directly into existing macropores leading to lower flow rates.

Among tillage treatments, higher flow rates were observed in RT and NT treatments than in the CT treatment, with NT exhibiting the highest flow rates. Except for the Rain2 event in CTNR, the maximum flow rate in the CT treatment was less than 0.5 m/day, while the maximum flow rates in NT and RT treatments were greater than 1.6 and 1 m/day, respectively. The NT and RT treatments usually contain macropores, either undisturbed and continuous (in NT) or with minimum disturbance (in RT) through which preferential flow of water may occur. This leads to higher flow rates in these tillage systems as we observed.

Nitrate-N in Drainage Water. Among the three tillage treatments, the highest [NO_3^--N] were observed in the water flow from the CT treatment where the lowest water flow rate occurred. In CT practices, the soil aggregates

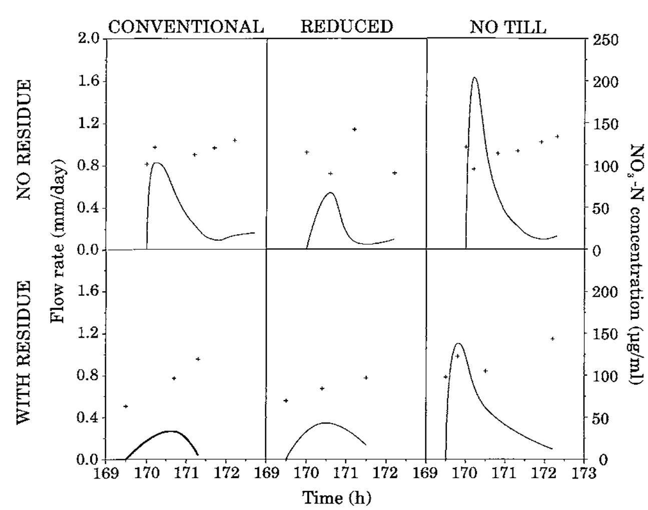

Figure 7–Nitrate-N concentration (+) in drainage water and flow rate (—–) for Rainfall 2 in experiment II.

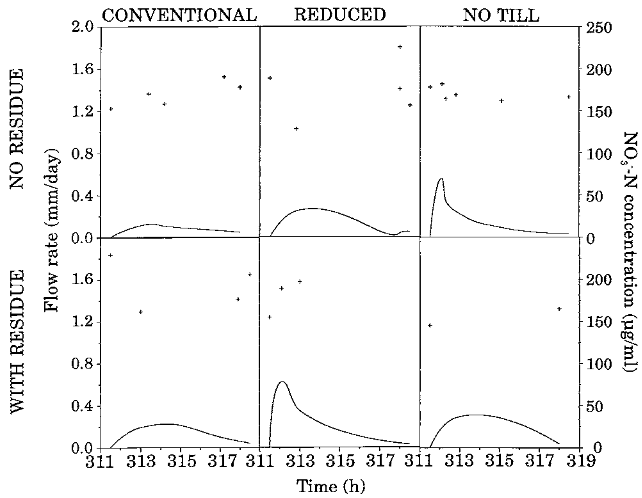

Figure 8–Nitrate-N concentration (+) in drainage water and flow rate (—–) for Rainfall 3 in experiment II.

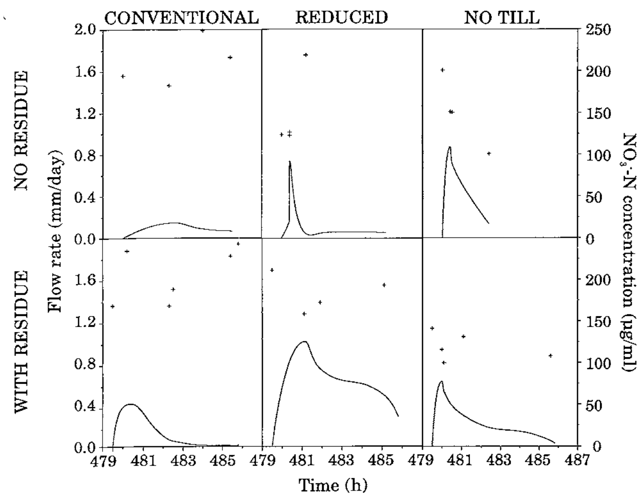

Figure 9–Nitrate-N concentration (+) in drainage water and flow rate (—–) for Rainfall 4 in experiment II.

become pulverized thus eliminating large pores and creating a more homogeneous system of smaller pores (Kanwar et al., 1985). This would expose more surface area to water movement, thus allowing more NO_3^--N to move with the water than when preferential flow occurs. Figures 6, 7, and 8 also indicate that the [NO_3^--N] in all treatments increased with each successive rain event. This increase indicates that water initially transported the applied NO_3^--N but further water applications transported also the residual NO_3^--N in the soil. According to the initial [NO_3^--N] in the soil at 6 h (fig. 4), in the CT treatment the soil layers 0.4 m deep and below had the highest [NO_3^--N]. This might explain why CT generally exhibited highest increases in [NO_3^--N] with each water application. The results indicate that CT practices would lead to deeper NO_3^--N leaching than NT or RT.

Conclusions

In experiment I, deeper leaching was observed in the NT treatment. In experiment II, deeper leaching occurred in the RT and CT treatments. Besides tillage, other leaching factors that may have caused these contradictory observations include the manner of fertilizer application (granular in experiment I; solution in experiment II), and dissimilar soil properties brought about by the time that elapsed between the two experiments. In experiment I, water in the NT treatment may flow through continuous macropores carrying with it dissolved fertilizer from the soil surface and result in deeper N leaching. The lower bulk densities and higher porosities in the tilled layers of RT and CT treatments in experiment I also favor greater water redistribution in the top layers, leading to less leaching to lower soil layers. In experiment II, the applied water/fertilizer solution is redistributed within the top layers of the RT and CT treatment, and water flow through macropores in the NT soil following subsequent water applications would bypass most of the fertilizer. Experiment II suggests that in situations where the nitrogen fertilizer is applied in solution, and subsequently followed by several water applications, NT practices retain higher NO_3^--N within the upper layers of the soil, while RT and CT encourage rapid deeper leaching.

Acknowledgments. This research was funded by grants from Fonds pour la Formation de Chercheurs et l'Aide à la Recherche du Québec (FCAR) and the Netherlands Government through the University of Nairobi, Kenya.

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