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Nitrate Leaching under Furrow Irrigation as Affected by Crop Sequence and Tillage

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ABSTRACT

The potential for NO_3-N leaching after alfalfa (*Medicago sativa* L.) in irrigated crop production depends on cropping sequence and tillage practices. A 2-yr field experiment in south-central Idaho compared the NO_3-N leached following alfalfa of a conventional tillage bean-bean (*Phaseolus vulgaris* L.) rotation with a silage corn (*Zea mays* L.)-winter wheat (*Triticum aestivum* L.) rotation in a conventional tillage or no-till system. Nitrate leaching was determined by: (i) sampling the soil solution below the root zone (1.2 and 1.5 m) using ceramic-tipped samplers and calculating the N movement from the water balance, and (ii) measuring the change in soil NO_3-N at 1.35 to 4.5 m from soil samples taken in the fall and spring to 4.5 m. During the second growing season, average soil solution NO_3-N concentrations (below the root zone) were 28, 4, and 10 mg L^{-1} for the bean-bean, corn-wheat no-till, and corn-wheat tilled treatments, respectively. The soil NO_3-N in 1.35 to 3.3 m at the end of the study was 80 kg N ha^{-1} higher for the bean-bean treatment than for the corn-wheat treatments. The NO_3-N that moved below 1.35 m during the 2 yr was 53 kg ha^{-1} higher for the bean-bean than for the corn-wheat treatments. The soil NO_3-N in the 1.35 to 3.3 m depth after 2 yr was 21 kg ha^{-1} higher for the corn-wheat under conventional tillage than under the no-till system.

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A COMMON CROPPING SEQUENCE in south-central Idaho includes alfalfa followed by 2 yr of bean. Large amounts of N can be mineralized after alfalfa especially during the first year (Meek et al., 1994). Cropping another legume such as bean after alfalfa inefficiently uses this N source. The crop sequence and tillage should also be modified so that crop N uptake synchronizes as closely as possible with the soil N mineralization rate (Carter et al., 1991). Efficiently using most of the N available for crop growth will reduce the potential for NO_3-N leaching into the groundwater from agricultural fields.

Endelman et al. (1974) showed that rainfall or irrigation can rapidly move NO_3-N beyond the rooting zone. Leaching of NO_3-N can be evaluated by measuring the NO_3-N concentration of the soil solution and by using water flux at the bottom of the root zone. The soil solution can be obtained with ceramic-tipped tubes, or the NO_3-N concentration can be determined on soil samples. The water flux can be estimated by calculating a water balance or by measuring the unsaturated soil

Abbreviations: ET, evapotranspiration; BT, bean tilled; CNT, corn no-till; WNT, wheat no-till; CT, corn tilled; WT, wheat tilled; LSD, least significant difference.

water flow rates (Robbins and Carter, 1980). The water balance can be calculated from changes in soil water content, water infiltrated into the soil, and ET. Evaporation can be estimated from lysimeter data and crop coefficients (Wright, 1982).

Ceramic-tipped solution samplers are used in many field studies to sample the soil solution for chemical analysis. Grossmann and Udluft (1991) stated that they could be installed with minimal soil disturbance and effort, but the bypass water flow through macropores can be a problem. Henderson and Courchesne (1991) found that the NO_3–N concentration was significantly lower in solution from a zero-tension sampler than that from a ceramic-cup tension sampler. Microbial activity in the ceramic-cup sampler after collecting the solutions might have caused the difference.

Soil samples can also be taken below the root zone before and after a study to evaluate NO_3–N leaching. The samples must be taken to a sufficient depth so that no NO_3–N was leached below the sampling depth during the study. Eck and Jones (1992) measured NO_3–N changes in a wheat–sorghum [*Sorghum bicolor* (L.) Moench]–fallow rotation for the 0- to 5-m depth and determined that NO_3–N leached deeper under no-till compared with tilled treatments.

The objectives of this study were to: (i) measure NO_3–N leaching below the root zone under three rotations following alfalfa (a silage corn–winter wheat rotation under a conventional tillage or no-till system and a bean-bean rotation), and (ii) compare the NO_3–N leached by (a) soil sampling techniques or (b) calculation of the NO_3–N leached using the water balance and the NO_3–N concentration in the soil solution.

MATERIALS AND METHODS

The experiment was conducted in south-central Idaho on a Portneuf silt loam (coarse-silty, mixed, mesic Durixerollic Calciorthid). Alfalfa was grown the previous 4 yr and was killed by an application of glyphosate [*N*-(phosphonomethyl)glycine] on 26 Oct. 1989. Treatments were BT–BT [bean grown in 1990 and 1991 under conventional tillage with no added N fertilizer; phosphorus (56 kg ha^{-1}) and Zn (11 kg ha^{-1}) applied to plots before planting in 1990], CNT–WNT [silage corn grown in 1990 and winter wheat in 1990–1991; both crops grown in a no-till system, planted into the killed alfalfa stubble with slight disturbances from planting and cleaning of the irrigation furrows; triple super phosphate (56 kg P ha^{-1}) applied to all plots before planting; urea applied to all plots planted to winter wheat in October 1990 at 82 kg N ha^{-1}], and CT–WT (silage corn grown in 1990 and winter wheat in the 1990–1991 season in a conventional-tillage system; same fertilizer treatments as the no-till system).

A more detailed description of the treatments and cultural operations was given by Meek et al. (1994). The field was divided into 18 plots, each 243 m long and either 8.8 m (bean) or 6.1 m wide (corn or wheat). The design consisted of three treatments and six replications in a randomized complete block. Urea was also applied to the corn and wheat plots on 19 Apr. 1990 and 9 Apr. 1991 in 9.1-m strips across the width of the field to evaluate the adequacy of N for optimum yield. It was applied at rates of 0, 82, and 164 kg N ha^{-1}.

Bean is commonly irrigated six to seven times during the season and once before planting. Preplant irrigations were not done in this study. Silage corn had 9 to 11 irrigations because of a longer growing season. Winter wheat had the least number of irrigations (one in the fall and four to five in the spring and summer) because part of the growing season is during the time with low ET and higher precipitation. Irrigation durations were adjusted to obtain leaching fractions around 40% of applied water, which is common for growers in this area. The entire length of each plot (243 m) was furrow irrigated. The inflow water in one of the center furrows in each plot was measured with a bucket and stopwatch; the runoff in the same furrow was measured with automated flumes. Corn was irrigated with water applied to every other furrow (0.76 m between furrows) with a change to alternate furrows in the middle of the growing season. Water was applied to all furrows in the bean crop, but furrows were between every other bean row (1.10 m between furrows). Irrigation furrows (0.76-m wide) were either cleaned out (no-till) or constructed (tilled) and every furrow irrigated for the winter wheat.

Measurements and samples to define the system were all taken near the center of the field in an area 79 to 103 m from the head end of the 243-m-long field, because it had about average leaching conditions. It was not possible to characterize leaching differences between the upper and lower parts of the field because of the large number of measurements needed.

Drainage (D) was calculated using the following formula: $D = -(\mathrm{ET}) + \text{precipitation} + \text{irrigation} + \text{change in soil water}$. Evapotransportation was calculated from weighing lysimeter data and crop coefficients (Wright, 1982). The lysimeter was located $\approx$2.4 km from the research plots. Irrigation water was the amount of water infiltrated. Soil water contents were measured 91 m from the upper end of the plots using a neutron moisture meter with tubes installed to 2.4 m. Readings were usually taken immediately before and 2 d after an irrigation. Only the soil water in the 0- to 1.35-m soil depth was used.

Solution samplers were installed both at the 1.2- and 1.5-m depths (two at each depth per plot, 0.45 m apart). They consisted of a ceramic cup (23-mm o.d., 60 mm long) sealed to a plastic tube of similar o.d. Samplers were installed by drilling a 24-mm-o.d. hole, putting a small amount of slurry (made with water using the soil) in the hole, and forcing the sampler into the hole. Samplers were placed in the ridge, which was never saturated so that there would be no flow of water down the side of the tube. Any water in the tube was removed before the samplers were placed under a vacuum. A tank evacuated to 19 kPa was attached 24 h to each sampler, usually after each irrigation. Sufficient solution was obtained for all analyses.

The plots were hydrologically isolated because they were nearly level (average slope 0.6%), the water table was below 4.5 m, and the soil was not saturated in the top 4.5 m except in the immediate vicinity of the irrigated furrow. The soil did not reach saturation because water movement was not restricted by soil layers and because irrigations were by widely spaced furrows.

Deep soil samples were taken in the fall and spring before and after each cropping season to 4.5 m. Six cores per plot were composited by 0.3-m depth increments. The composited samples were screened (3.5-mm mesh screen) and mixed, and a subsample was frozen for later analysis.

Macropores were measured at the 0.15-m depth in September 1991. Metal cylinders (0.2-m diam.) were positioned over the furrows and driven 0.15 m into the soil. When the measurements were made, the soil had cracked so the surface seal in the furrow was disrupted. A 5 g kg^{-1} aqueous solution (1 L) of methylene blue was added to each cylinder and allowed to infiltrate. The solution infiltrated about 20 min. The cylinders

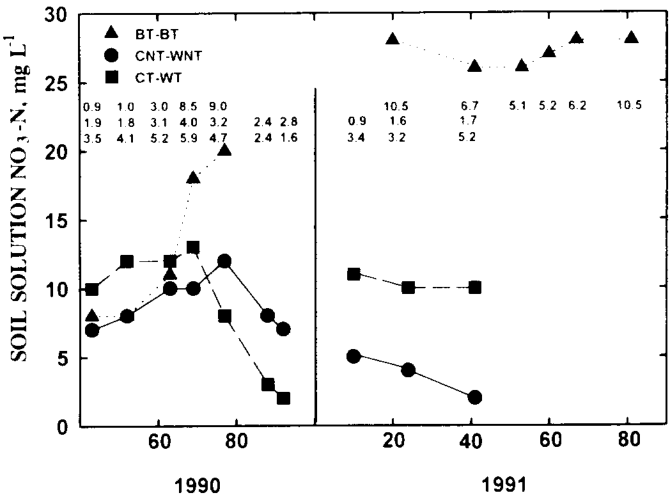

Fig. 1. Nitrate-nitrogen concentration of soil solutions collected using ceramic-tipped samplers (average of values measured at 1.2- and 1.5-m depths) in 1990 and 1991. Numbers indicate standard deviation in same order as treatments listed in legend; BT = no-till bean, CNT = no-till corn; WNT = no-till wheat; CT = conventionally tilled corn; WT = conventionally tilled wheat.

were dug out and turned so that the bottom was up, and the stained pores were counted. One measurement was made in each plot.

Soil samples were extracted with 2 *M* KCl (10 g soil to 0.05 L of extracting solution), shaken for 30 min, and filtered. Nitrate and NH_4 were analyzed with a Lachat QuickChem AE[1] using Methods 12-107-06-2-A (Cd reduction) and 12-107-04-1-B (salicylate procedure), respectively (Lachat Instruments, 1993). Soil solution samples were analyzed directly for NO_3-N.

[1] Trade names are provided for the benefit of the reader and do not imply any endorsement by the U.S. Department of Agriculture.

Selected data were analyzed by analysis of variance. Duncan's multiple-range test ($P \leq 0.05$) was used to separate means when the *F* test showed statistical significance. Standard deviations were calculated for some of the measurements and significant differences were determined by the *t*-test ($P \leq 0.05$).

RESULTS

The NO_3-N concentrations in the soil solutions were similar in all treatments when the experiment started in the summer of 1990; the concentration in the BT-BT treatment was much higher the last part of the 1990 season and all during the 1991 season (Fig. 1). The data represents the average of solution concentrations at 1.2- and 1.5-m depths (4 values × 6 plots). The 1990 NO_3-N concentrations were not significantly different (LSD, 0.05) until the end of the season. The NO_3-N concentration in the BT-BT treatment was higher than both CT-WT and CNT-WNT on 18 August (78 d after 1 June 1990). The CNT-WNT treatment was higher than CT-WT on 28 Aug. and 1 Sept. 1990. The average NO_3-N concentration in the soil solution during the summer of 1991 was 27, 4, and 10 mg kg^{-1} for the BT-BT, CNT-WNT, and CT-WT treatments, respectively. In 1991, the tilled wheat (CT-WT) had significantly higher NO_3-N in the soil solution than the no-till wheat (CNT-WNT) at all sampling dates.

The soil NO_3-N concentration peaked in the 0- to 0.45-m depth on about Day of the Year 160 (Fig. 2). Five irrigations moved this NO_3-N peak to the 1.2-m soil solution sampler (≈ 0.2 m movement per irrigation). The peak was also fairly distinct at the 1.5-m depth because the soil solution NO_3-N concentration doubled as the peak moved by.

The application of 164 kg N ha^{-1} in April 1990 increased soil NO_3-N to 2.25 m (LSD, 0.05) when sampled

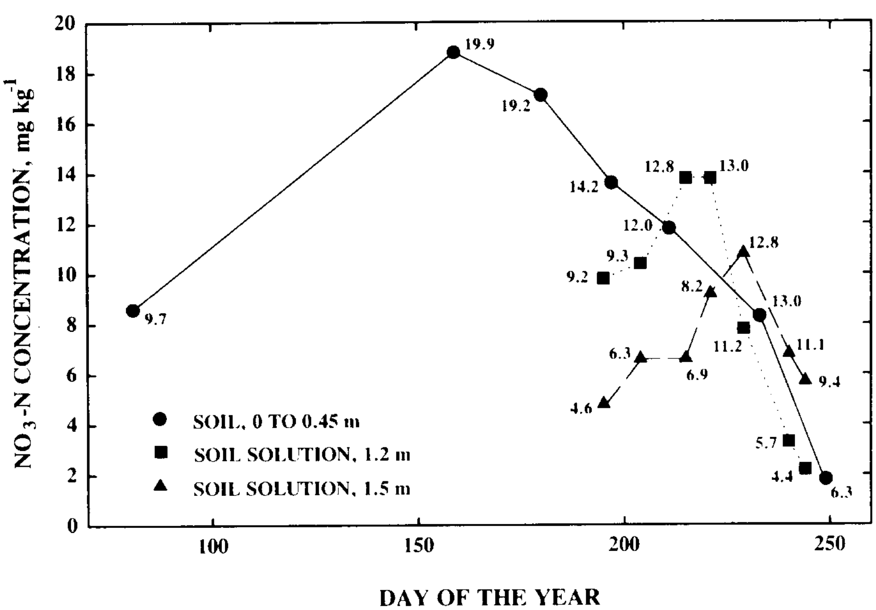

Fig. 2. Comparison of changes in NO_3-N concentration (average of no-till corn-wheat and conventionally tilled corn-wheat) in 1990 with time for the soil (0-0.45 m) and the soil solution at the 1.2- and 1.5-m depths. Numbers next to symbols are standard deviations.

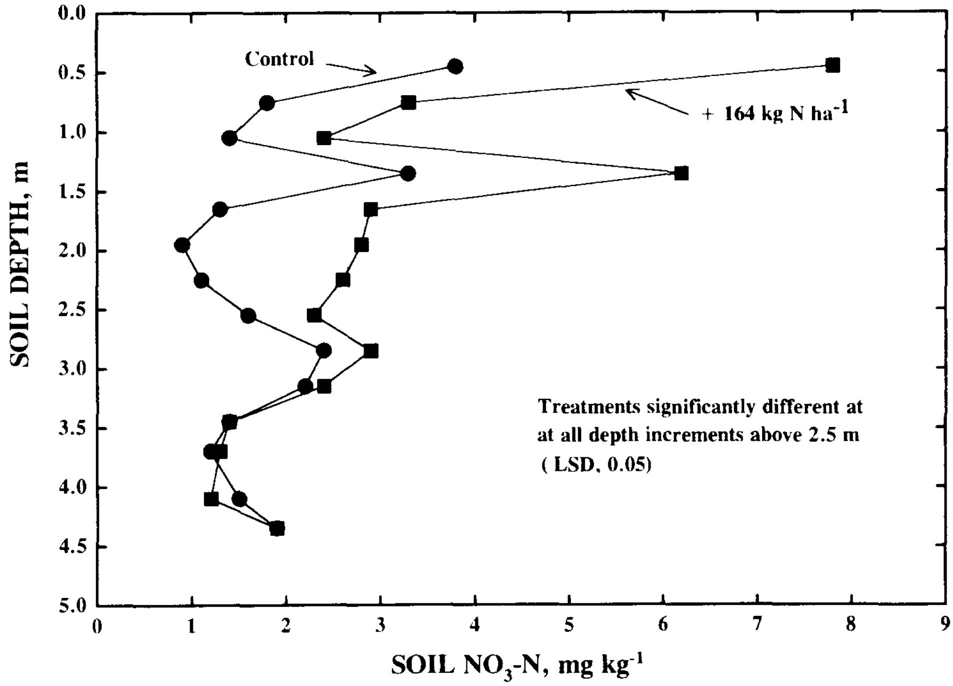

Fig. 3. Soil NO_3-N in the conventionally tilled corn-wheat treatment when urea was applied at 0 or 164 kg N ha^{-1} in April 1990 (sampled in March 1991).

in March 1991 (Fig. 3). Because 11 irrigations had occurred in the time elapsed, the NO_3-N moved about 0.2 m per irrigation. The relatively high soil NO_3-N concentration in the root zone and subsequent peak at 1.35 m in March 1991 were apparently caused by N mineralization in the fall 1989 and spring 1990 and by the spring 1990 N fertilizer application.

Nitrate-N concentrations in the 0- to 0.45-m soil depth were used to estimate the concentrations that would be measured in the soil solution (Table 1). Soil NO_3-N concentrations are from Meek et al. (1994). A concentration of 20 mg N kg^{-1} in the soil would be equivalent to a concentration of 81 mg N L^{-1} in the soil solution (soil bulk density of 1.33 Mg m^{-3}, with a volumetric water content of 0.33 m^3 m^{-3}). The NO_3-N concentration

Table 1. Comparison of the NO_3-N in the soil with that in the soil solution below the root zone.

	NO_3-N	
Treatment	Soil 0 to 0.45 m May, June, July†	Soil solution avg. of 1.2 and 1.5 m June, July, August
	mg kg^{-1}	mg L^{-1}
Corn (1990)		
No-till	14 (56)‡	9
Tilled	19 (77)	10
Wheat (1991)		
No-till	4 (16)	4
Tilled	6 (24)	10
Beans		
1990	26 (105)	12
1991	33 (133)	27

† Used different times to compensate for the time necessary for the soil solution to flow from the surface to the 1.2- to 1.5-m depth (Meek et al., 1994).

‡ Estimated NO_3-N in the soil solution (soil NO_3-N × 4.03 [1.33 Mg m^{-3} bulk density and 0.33 m^3 m^{-3} volumetric water content]).

in the soil solution appears to decrease from the surface to the 1.2- or 1.5-m depth. This change may be caused by a combination of higher N mineralization levels in, and crop N uptake from, the surface soil and some dilution at the lower depths.

There were no differences (Duncan's multiple-range test, 0.05) in soil NO_3-N concentrations between treatments in March 1990, but large differences existed in September 1991 (Table 2). Soil NO_3-N in the upper soil profile (0–1.2 m) after one season (October 1990) was similar between treatments. The only significant differences were at the 1.2- to 2.1-m depth, with CT–WT being higher at the 1.2- to 1.5- and 1.5- to 1.8-m depth increments and BT–BT being higher at the 1.8- to 2.1-m depth. Soil NO_3-N in the soil profile after two seasons (September 1991) was significantly higher in BT–BT compared with the other treatments for each of the depths analyzed within 0.9 to 3.3 m. For the 0.9- to 3.3-m depth, there was an increase of 94 kg N ha^{-1} in BT–BT compared with an average of 136 kg N ha^{-1} for the other two treatments.

When larger depth increments were analyzed (0–3.30, 0–4.50, 1.35–3.30, or 1.35–4.5 m; Table 2), no differences were observed between treatments within a date except for September 1991. Soil NO_3-N below 1.35 m increased with time (October 1990–September 1991) in BT–BT but decreased in the other two treatments. In September 1991, BT–BT contained more NO_3-N than either of the other two treatments at each of the larger depth increments. There was also a significantly greater amount of NO_3-N in CT–WT than in CNT–WNT at the 1.35- to 3.3-m depth.

Using the amount of water leached below 1.35 m and the NO_3-N concentration of samples collected with

Table 2. Soil NO_3-N present as a function of sampling depth and treatment (B = bean, C = corn, W = winter wheat, T = conventional tillage, NT = no-till).

Depth interval	March 1990 (Avg. three treatments)	October 1990			March 1991			September 1991		
		BT-BT	CNT-WNT	CT-WT	BT-BT	CNT-WNT	CT-WT	BT-BT	CNT-WNT	CT-WT
m	kg ha⁻¹									
0-0.3	52	57	47	60	117	131	174	101a	45b	52b
0.3-0.6	30	19	14	14	26	31	31	19	15	18
0.6-0.9	18	21	20	19	23a	16b	19b	22	14	18
0.9-1.2	18	24	18	20	26a	18b	19b	25a	14b	18b
1.2-1.5	19	30a†	25a	41b	29	20	25	27a	15b	19b
1.5-1.8	19	26a	29a	52b	26	19	24	33a	15b	19b
1.8-2.1	16	19b	13a	12a	23a	17b	16b	27a	14b	18b
2.1-2.4	16	18	17	16	23	17	18	29a	15b	19b
2.4-2.7	17	17	17	17	21	19	18	29a	16b	19b
2.7-3.0	17	18	27	23	20	20	21	25a	16b	19b
3.0-3.3	17	27	34	20	21	18	22	34a	17b	19b
3.3-3.6	Not sampled	15	18	17	17	18	18	20	15	18
3.6-3.9	Not sampled	14	12	14	16	17	18	22	16	19
3.9-4.2	Not sampled	14	14	17	17	17	19	22	16	18
4.2-4.5	Not sampled	14	14	17	17	17	21	22	17	21
SUM										
0-3.3	238	276	262	294	354	325	387	371a	198b	239b
0-4 5		334	320	359	420	263	315	457a	263b	315b
1.35-3.3‡	112	140	150	153	149	120	132	191a	101c	122b
1.35-4.5		197	208	218	216	189	208	277a	165b	198b

† Row values within a date followed by a different letter are significantly different (Duncan's multiple-range test, 0.05 level).
‡ One-half of the NO_3-N content for the interval between 1.2 and 1.5 m was taken to obtain a break at 1.35-m depth. This depth was used because it was the average depth of the solution samplers.

ceramic-tipped solution samplers, an estimate of N movement was calculated (Tables 3-5). Leaching fractions (water drained below the root zone/water infiltrated) were between 0.37 and 0.48. The NO_3-N movement below 1.35 m for the first year (March to October 1990) was 42, 43, and 33 kg N ha^{-1} for the BT-BT, CNT-WNT, and CT-WT treatments, respectively. The NO_3-N movement below 1.35 m for the second year (March-September 1991) was 67, 13, and 29 kg N ha^{-1} for the BT-BT, CNT-WNT, and CT-WT treatments, respectively. The total NO_3-N movement below 1.35 m during the 2 yr (1 Apr. 1990-10 Sept. 1991) was 121, 64, and 70 kg N ha^{-1} for the BT-BT, CNT-WNT, and CT-WT treatments, respectively.

DISCUSSION

The leaching of NO_3-N below the root zone in this study was similar to that determined by Robbins and Carter (1980). They conducted research under almost

Table 3. Water and N balance for the top 1.35 m of soil (BT-BT = bean-bean, tilled treatment; ET = evapotranspiration).

Time interval	Soil crop cover status†	Water applied		Change in soil water 0-1.35 m		ET	Drainage water leached‡ below 1.35 m	NO_3-N in soil solution§	NO_3-N leached‡ below 1.35 m
		Irrigation	Rain	Initial	Final				
		mm						mg N kg⁻¹	kg ha⁻¹
				1990					
1 Apr. to 12 June	Bare	0	108	328	338	113	0	7.5	
12 June to 29 June	Seedling	87	5	338	411	49	0	7.5	
29 June to 12 July	Partial	48	0	411	410	65	0	7.5	
12 July to 19 July	Full	54	0	410	431	53	0	8	
19 July to 26 July	Full	61	1	431	445	56	0	8.4	
26 July to 3 Aug.	Full	73	0	445	460	64	6	11.4	1
3 Aug. to 10 Aug.	Full	110	0	460	465	50	55	17.7	10
10 Aug. to 18 Oct.	Cut	97	17	465	371	53	155	20	31
Totals		530	131			503	216		42
				Winter 1990-1991					
18 Oct. to 25 Mar.	Bare	0	109	371	306	125	49	24	12
				1991					
25 Mar. to 14 June	Plant	0	67	306	326	115	0	26	
14 June to 19 June	Seedling	78	0	326	374	18	12	28	3
19 June to 12 July	Partial	97	13	374	402	70	12	26	3
12 July to 24 July	Full	59	0	402	389	69	3	26	1
24 July to 31 July	Full	114	0	389	450	47	6	27	2
31 July to 7 Aug.	Full	153	0	450	491	50	62	28	17
7 Aug. to 14 Aug.	Full	82	0	491	476	49	48	28	13
14 Aug. to 21 Aug.	Full	79	0	476	478	41	36	28	10
21 Aug. to 10 Sept.	Cut	0	30	478	377	67	63	28	18
Totals		662	110			526	242		67

† Full cover: 1990 = July 20; 1991 = July 15. Cut: 1990 = Sept. 12; 1991 = Sept. 20. Plant: 1990 = June 4; 1991 = June 4.
‡ Leaching fraction: April to October 1990 = 0.41; March to October 1991 = 0.37.
§ From ceramic-tipped samplers, average of 1.2 and 1.5 m.

Table 4. Water and N balance for the top 1.35 m of soil (CNT–WNT = Corn–winter wheat, no-till treatment; ET = evapotranspiration).

Time interval	Soil crop cover status†	Water applied: Irrigation‡	Water applied: Rain	Change in soil water 0–1.35 m: Initial	Change in soil water 0–1.35 m: Final	ET	Drainage water leached§ below 1.35 m	NO_3-N in soil solution¶	NO_3-N leached§ below 1.35 m
		mm						mg N kg⁻¹ → $mg\ N\ kg^{-1}$	$kg\ ha^{-1}$
				1990					
1 Apr. to 12 June	Bare	112	108	328	362	121	65	6.9	5
12 June to 28 June	Seedling	56	5	362	380	54	0	6.9	
28 June to 13 July	Partial	45	0	380	355	86	0	6.9	
13 July to 26 July	Full	108	1	355	324	104	36	7.8	3
26 July to 3 Aug.	Full	151	0	324	447	65	0	9.8	
3 Aug. to 10 Aug.	Full	124	0	447	480	52	39	10.5	4
10 Aug. to 16 Oct.	Harvest	384	15	480	311	227	341	9	31
16 Oct. to 18 Oct.	Bare	145	2	311	481	9	0	6.8	
Totals		1125	131			718	481		43
				Winter 1990–1991					
18 Oct. to 25 Mar.	Bare	0	109	481	333	143	114	6.8	8
				1991					
25 Mar. to 29 May	Seedling	125	55	333	326	157	30	6.0	2
29 May to 8 June	Partial	228	12	326	464	54	48	5.3	3
8 June to 24 June	Full	232	0	464	470	112	126	3.7	5
24 June to 12 July	Full	214	13	470	443	118	136	2	3
12 July to 2 Aug.	Full	0	0	443	363	103	0	2	
2 Aug. to 10 Sept.	Harvest	0	30	363	269	35	0	2	
Totals		799	110			579	340		13

† Full cover: 1990 = July 15; 1991 = June 14. Harvest: 1990 = Sept. 29; 1991 = Sept. 3.
‡ 3 Aug. 1990 to 16 Oct. 1991 - three irrigations were applied. The neutron probe was inoperative so readings were not obtained after two of the irrigations.
§ Leaching fraction: 1 Apr. to Oct. 1990 = 0.43; Mar. to Sept. 1991 = 0.37.
¶ From ceramic-tipped samplers, average of 1.2 and 1.5 m.

the same conditions, estimated NO_3-N leaching from soil NO_3-N concentrations below the root zone, and calculated unsaturated soil water flow rates. They estimated that 113 kg ha^{-1} of NO_3-N leached below the root zone when two consecutive bean crops followed alfalfa, compared with 121 kg ha^{-1} measured in this study. When corn followed alfalfa, they estimated a loss of 60 kg N ha^{-1}, compared with an average of 39 kg N ha^{-1} measured in this study. For the sequence alfalfa-bean–wheat, they estimated a loss of 29 kg N ha^{-1} for spring wheat, compared with losses (October to September) of 37 (CT–WT) and 21 kg N ha^{-1} (CNT–WNT) for winter wheat in the sequence alfalfa–silage corn-wheat in this study.

The NO_3-N moving past 1.35 m during the 2 yr was 54 kg ha^{-1} larger for BT–BT than the average of 67 kg N ha^{-1} for the other treatments. Soil NO_3-N between 1.35 and 3.3 m was also 80 kg ha^{-1} higher for BT–BT

Table 5. Water and N balance for the top 1.35 m of soil (CT–WT = corn–winter wheat, tilled treatment; ET = evapotranspiration).

Time interval	Soil crop cover status†	Water applied: Irrigation‡	Water applied: + Rain	Change in soil water 0–1.35 m: Initial	Change in soil water 0–1.35 m: Final	ET	Drainage water leached§ below 1.35 m	NO_3-N in soil solution¶	NO_3-N leached§ below 1.35 m
		mm						$mg\ N\ kg^{-1}$	$kg\ ha^{-1}$
				1990					
1 Apr. to 12 June	Bare	128	108	324	381	121	58	9.8	6
12 June to 28 June	Seedling	44	5	381	397	54	21	9.8	2
28 June to 13 July	Partial	50	0	397	318	86	43	9.8	4
13 July to 26 July	Full	129	1	318	389	104	0	11.6	
26 July to 3 Aug.	Full	136	0	389	475	65	0	12	
3 Aug. to 10 Aug.	Full	143	0	475	534	52	32	13	4
10 Aug. to 16 Oct.	Harvest	433	15	534	339	227	416	4.2	17
16 Oct. to 20 Oct.	Bare	160	2	339	478	9	12	2	
Totals		1223	131			718	582		33
				Winter 1990–1991					
20 Oct. to 25 Mar.	Bare	0	109	478	327	143	117	6.5	8
				1991					
25 Mar. to 29 May	Seedling	124	55	327	328	157	21	11	2
29 May to 7 June	Partial	197	12	328	437	54	46	11	5
29 May to 7 June	Full	224	0	437	437	112	112	9.9	12
7 June to 24 June	Full	186	13	437	448	118	70	9.5	7
12 July to 2 Aug.	Full	0	0	448	354	103	0	9.5	
2 Aug. to 10 Sept.	Harvest	0	30	354	317	35	32	9.5	3
Totals		731	110			579	281		29

† Full cover: 1990 = July 15; 1991 = June 14. Harvest: 1990 = Sept. 29; 1991 = Sept. 3.
‡ Three irrigations were applied 3 Aug. 1990 to 16 Oct. 1991. The neutron probe was inoperative so readings were not obtained after two of the irrigations.
§ Leaching fraction: Apr. to Oct. 90 = 0.48; Mar. to Sept. 1991 = 0.38.
¶ From ceramic-tipped samplers, average of 1.2 and 1.5 m.

Table 6. Comparison of calculated NO_3-N movement below the root zone and change in soil NO_3-N from 1.35 to 3.3 m (March-April 1990 to September 1991).†

	Treatments‡		
	BT-BT	CT-WT	CNT-WNT
	kg N ha^{-1}		
Movement below 1.35 m	121	70	64
Change in soil NO_3-N 1.35-3.3 m			
(Change compared with BT-BT)	+79	+10	−11
Movement		−51	−55
Soil NO_3-N		−69	−89

† Soil samples taken 9 Mar.-4 Apr. 1990 and 23 Sept.-1 Oct. 1991. Nitrogen flux calculated from 1 Apr. 1990-10 Sept. 1991.
‡ BT-BT = bean-bean, tillage treatment; CT-WT = corn-wheat, tillage treatment; CNT-WNT = corn-wheat, no-till treatment.

compared with 111 kg N ha^{-1} for the average of the other two treatments. The delayed N uptake of beans compared with that for winter wheat and their reduced total N uptake compared with that of silage corn were probably important factors contributing to greater NO_3-N leaching in the BT-BT treatment. The soil NO_3-N increase in the 1.35- to 3.3-m depth for BT-BT compared with the average of the other two treatments was larger than the amount of N (53 kg ha^{-1}) that leached below 1.35 m in the BT-BT treatment. If the BT-BT treatment had been preplant irrigated, even more NO_3-N leaching below the root zone would probably have occurred.

The soil NO_3-N concentrations were similar in 1990 and 1991 for the CNT-WNT and CT-WT treatments (Meek et al., 1994), but the concentration of NO_3-N in the soil solution below the root zone in 1991 for CT-WT was double the concentration in CNT-WNT. The difference in NO_3-N leaching between BT-BT and CT-WT determined either by measuring NO_3-N movement (−51 kg N ha^{-1}) or by change in soil NO_3-N below the root zone (−69 kg N ha^{-1}) were comparable (Table 6). In contrast, the difference between BT-BT and CNT-WNT was higher when determined by change in soil NO_3-N (−89 kg N ha^{-1}) than when measured by NO_3-N movement (−55 kg N ha^{-1}). There were twice as many continuous pores ≥1 mm in diameter at 0.15 m in the CNT-WNT treatment at the end of the second year compared with CT-WT (Data not shown). The ceramic-tipped samplers may collect a disproportionately larger amount of water moving through the larger pores. This water may have a lower NO_3-N concentration because of dilution and because NO_3-N in the smaller pores was bypassed. Kanwar et al. (1985) showed that, after a 0.127-m rain, 40% of the NO_3-N initially present (0-0.3 m depth) remained in the no-till treatment but only 19% remained in a plowed treatment.

The differential leaching of NO_3-N through the 1.35-m zone could be estimated by soil sampling to 4.5 m in this study because it appears that NO_3-N did not move below 4.5 m (Table 2). There were no significant differences in soil NO_3-N concentrations below 3.3 m. Also, measurements indicated that each irrigation moved the NO_3-N peak ≈0.2 m. Treatments that received 14 to 15 irrigations during the experiment would have leached NO_3-N to 2.8 to 3.0 m.

CONCLUSIONS

This study measured NO_3-N leaching as affected by crop sequence and tillage. Greater leaching occurred in the bean-bean rotation than in the silage corn-winter wheat rotation and with conventional tillage than with no-till. These findings demonstrate that NO_3-N leaching can be estimated by soil solution samplers or by taking deep soil cores under conventional tillage systems. For no-till systems, less NO_3-N leaching was estimated by a water balance and soil solution sampling method than by measuring soil NO_3-N concentrations below the root zone.

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