SOILS

Ammonium and Nitrate Nitrogen in Soil Profiles of Long-Term Winter Wheat Fertilization Experiments

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ABSTRACT

Accumulation of NH_4^+-N and NO_3^--N in soils has not been thoroughly evaluated in long-term continuous winter wheat (*Triticum aestivum* L.) production systems. The objectives of this study were to determine long-term response of winter wheat to N fertilization and to evaluate accumulation of NH_4^+-N and NO_3^--N in the soil profile. Four long-term winter wheat soil fertility experiments on thermic Ustoll soils that received annual applications of N for >18 yr at selected N rates were sampled. At each location, one soil core 4.4 cm in diameter was taken to a depth of 240 cm from plots receiving variable N rates. Cores were separated into 30-cm increments and analyzed for 2 *M* KCl-extractable NH_4^+-N and NO_3^--N. At all locations, NH_4^+-N levels were not significantly different from the check (no fertilizer N) when rates were applied at or below yield goal requirements (90 or 45 kg N ha^{-1} vs. 0 N). At N rates >90 kg N ha^{-1}, surface (0–15 cm) NH_4^+-N increased compared with the check, while subsurface NH_4^+-N did not. Similarly, when N rates were <90 kg N ha^{-1}, no significant differences in either surface or subsurface NO_3^--N were found. At N rates >90 kg N ha^{-1}, NO_3^--N accumulated in the subsurface soil profile (>30 cm). Estimates of N rates determined from simultaneous solutions of NO_3^--N accumulation minimums and yield maximums generated from quadratic regression were greater than N rates currently recommended to achieve yield goals at all locations. For these long-term continuous winter wheat experiments, no accumulation of NH_4^+-N and NO_3^--N occurred at recommended N rates where near maximum yields were obtained.

Past and present use of N fertilizers for winter wheat production has been related to the potential for NO_3^--N contamination of surface and subsurface water. Although N fertilizers are essential for economic grain production, long-term N accumulation as a result of excessive N rates has not been monitored closely.

Work by Liang et al. (1991) found that residual soil NO_3^--N did not increase in the soil profile (0–60 cm) over a 4-yr period when comparing N rates of 170 and 400 kg ha^{-1} applied to corn. MacDonald et al. (1989) indicated that following harvest, unfertilized wheat plots had inorganic N contents equal to those where 234 kg N ha^{-1} had been applied. This work further suggested that almost all of the NO_3^--N at risk to leaching over the winter period comes from mineralization of organic N and not from unused fertilizer applied in the spring; therefore, even a drastic reduction in N fertilizer use would have little effect on NO_3^--N leaching. Lamb et al. (1985) reported that the addition of N fertilizer increased the amount of NO_3^--N accumulated but did not change the accumulation pattern. Tillage system (no-till, stubble mulch, and plow) did not affect the time at which the NO_3^--N started to accumulate during the fallow period nor the rate of accumulation (Lamb et al., 1985). Sharpley et al. (1991) reported no evidence of N accumulation in the soil profile (0–180 cm) after 5 yr for either no-till or reduced-till cultural practices with N fertilizer applied to sorghum at recommended rates (0–146 kg N ha^{-1} yr^{-1}), although annual total N in surface runoff was 0.76 kg N ha^{-1} for no-till, 0.99 kg N ha^{-1} for reduced-till, and 7.28 kg N ha^{-1} for conventional till. Smika (1990) reported that time must be allowed for the equilibration of soil conditions before evaluating NO_3^--N accumulation, citing research that showed less NO_3^--N accumulation to 120 cm for reduced-till methods compared with conventional tillage for short-term studies, but more NO_3^--N accumulation for reduced-till methods in long-term studies. Tracy et al. (1990) noted that tillage method (conventional, no-till) did not affect NO_3^--N accumulation below 5 cm; differences in NO_3^--N in the topsoil were attributed to organic matter incorporation over 16 yr of winter wheat farming. Varvel and Peterson (1990) reported that high N application rates (180 kg N ha^{-1}) resulted in greater residual soil NO_3^--N to 150 cm for continuous corn and grain sorghum systems than for other cropping systems. This same study found that all systems had similar NO_3^--N accumulation at lower N application rates.

Work by Liang et al. (1991) found that under irrigation, 100 kg NO_3^--N ha^{-1} was lost from the rooting zone (0–60 cm) during four growing seasons, with the majority coming from the surface 40 cm. The effects of N fertilizer rate (90 and 180 kg ha^{-1}) and nitrification inhibitors on urea ^{15}N leaching and balance on a irrigated sandy loam were summarized by Walters and Malzer (1990). The higher N application rate resulted in 3.4 times more N leached over a 3-yr period (206 vs. 88 kg ha^{-1} to 1.2 m depth). Nitrification inhibitors delayed N losses, but did not decrease the total N lost. Westerman and Tucker (1979) noted that the presence of organic residue can lower denitrification by increased immobilization of inorganic or mineralized N. Immobilization was thus considered to be an N conserving process competing with denitrification for nitrate.

Nitrate studies in field microplots showed that 17% of applied ^{15}N (120 kg N ha^{-1} equivalent) was still in the 45-cm soil profile after 1 yr (Kowalenko, 1989). Webster et al. (1986) evaluated the movement of ^{15}N (92 and 102 kg NH_4NO_3 ha^{-1}) in clay and sandy loam field microplots and found that <1% of the fertilizer was leached beyond 130 cm in the first winter following application.

Response of wheat grain yields to N fertilization has been documented in numerous soil fertility experiments. However, very few of these experiments have included evaluation for more than 3 to 5 yr that also accounted for accumulation of NO_3^--N and NH_4^+-N within the soil profile. The objectives of this study were to determine the long-term response of

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Table 1. Experiments included in the analysis of NH_4-N and NO_3-N in soil profiles under long-term fertilization, with year established, experimental design, soil core sampling date, and crop years prior to sampling.

Experiment†	Year established	Replications	Date sampled	Crop years prior to sampling	Plot size	Harvest area	Annual rainfall‡	
							Average	Range
		no.			m²		mm yr⁻¹	
222	1969	4	9 Sept. 1988	19	111.5	55.7	817	584–1397
406	1965	6	29 Sept. 1988	23	104.1	55.7	611	279–1143
502	1970	4	20 Sept. 1988	18	89.2	55.7	821	483–1321
505	1970	3	27 July 1990	20	59.4	37.2	821	483–1323

† Randomized complete block design in all experiments.

‡ Obtained from years each study was conducted.

winter wheat to N fertilization and to evaluate associated accumulation of NH_4^+–N and NO_3^-–N in the soil profile.

MATERIALS AND METHODS

Four long-term winter wheat (*Triticum aestivum* L.) fertility experiments were sampled to determine accumulation of NH_4^+–N and NO_3^-–N within the soil profile. The four experiments are identified as 222, 406, 502, and 505. Experiments 502 and 505 were separate studies conducted at the same location and on the same soil type. Soil types were Kirkland silt loam (fine, mixed, thermic Udertic Paleustoll), Tillman clay loam (fine, mixed, thermic Typic Paleustoll) and Grant silt loam (fine-silty, mixed, thermic Udic Argiustoll) for Experiments 222, 406 and 502, and 505, respectively. Additional site information is provided in Table 1. Initial soil test characteristics in given years for selective treatments are listed by location in Table 2. Winter wheat was planted in 25.4 cm rows at seeding rates of 67 kg ha⁻¹ at all locations. All fertilizers were broadcast and disk incorporated 10 to 15 d prior to planting, which took place from late September to mid October. At all locations, N, P, and K sources were NH_4NO_3 (34–0–0), triple superphosphate (0–20–0), and KCl (0–0–56), respectively. Cross-plot contamination was minimized in all experiments via the use of shallow disking parallel with plot length. Fertilizer treatments from each experiment are defined in Table 3.

One soil core from each plot, 4.45 cm in diameter, was taken to a depth of 240 cm and split into 10 increments: 0–15, 15–30, 30–45, 45–60, 60–90, 90–120, 120–150, 150–180, 180–210, and 210–240 cm. Two additional depths (240–270 and 270–300 cm) were taken from Experiment 505. Sampling dates for each experiment are listed in Table 1. Although all the long-term experiments are being continued, only grain yield data obtained prior to deep soil core sampling was used. In order to be consistent with the 30-cm depth increments used beyond 60 cm, the first four depth-increment samples were combined into two, comprising the 0 to 30 and the 30 to 60 cm depths. Soil samples were air-dried at ambient temperature and ground to pass a 20-mesh screen. Duplicate samples were extracted using 2 *M* KCl (Bremner, 1965) and analyzed for NH_4–N and NO_3–N using automated flow injection analysis (Lachat, 1989, 1990). Soil cores from check plots were examined for the presence of free $CaCO_3$ with a 10% (v/v) HCl solution.

The center 3.05 m of each plot was harvested for grain yield using a conventional self-propelled combine, and wheat straw was uniformly redistributed in all plots each year. Conventional statistical analysis on grain yield over years employed a split-plot-in-time design, since the same fertilizer treatments were applied each year to the same plots. Consistent with McIntosh (1983), considering year and treatments as random and fixed effects, respectively, the appropriate tests of hypothesis were made. Analysis of variance for soil NH_4^+–N and NO_3^-–N in kg ha⁻¹ per profile increment (calculated based on measured mineral N concentration and bulk density) was accomplished by using a split-plot-in-space design with depth being the split variable.

Table 2. Soil test characteristics (0–15 cm) for selected treatments and years for experiments 222, 406, 502 and 505.†

Experiment	N Rate	Year	pH	P	K	Organic C	Total N
	kg ha⁻¹			mg kg⁻¹		g kg⁻¹	
222	0	1981	5.2	44	179	—	—
		1988	5.8	70	211	6.4	0.67
	90	1981	5.0	30	183	—	—
		1988	5.5	38	209	8.3	0.82
406	0	1981	6.9	16	400	—	—
		1988	6.9	21	482	8.1	1.00
	90	1981	6.8	57	438	—	—
		1988	6.5	53	472	8.4	0.67
502	0	1980	5.7	33	287	—	—
		1988	5.0	45	320	7.1	0.62
	112	1980	5.3	73	411	—	—
		1988	4.6	73	392	5.8	0.63
505	0	1976	5.4	70	250	—	—
		1988	4.9	83	327	5.6	0.79
	134	1976	5.3	70	295	—	—
		1988	4.4	93	355	6.3	0.93

† pH, 1:1 soil:water; K, 1 *M* NH_4Ac extraction; P, Bray-Kurtz P-1; organic C and total N, dry combustion.

Table 3. Treatments sampled from each long-term experiment, and overall grain yield means.

Experiment	Fertilizer applied			Grain yield	
	N	P	K	Mean	SED†
	kg ha⁻¹ yr⁻¹			Mg ha⁻¹	
222	0	29	38	1.48	0.20
	45	29	38	1.87	
	90	29	38	1.93	
	134	29	38	1.97	
406	0	0	0	1.51	0.23
	45	20	38	2.06	
	90	20	38	2.17	
	134	20	38	1.90	
	179	20	38	1.89	
502	0	20	56	1.80	0.19
	22	20	56	2.36	
	45	20	56	2.52	
	67	20	56	2.72	
	90	20	56	2.81	
	112	20	56	2.67	
505	0	29	56	1.64	0.24
	34	29	56	2.39	
	67	29	56	2.63	
	134	29	56	2.73	
	269	29	56	2.59	

† SED, standard error of the difference.

Because all experiments included a quantitative factor (N rate), mean separation (e.g., LSD, DMRT) was not employed (Swallow, 1984). For reference purposes, the standard error of the difference (SED) between two means using the overall

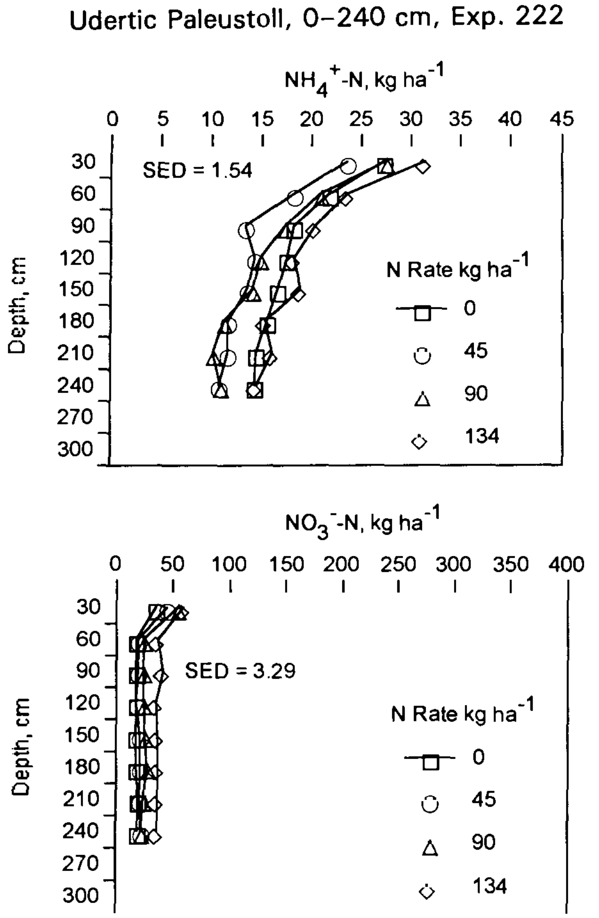

Fig. 1. Soil NH_4^+-N and NO_3^--N in kg ha^{-1} per profile increment as a function of N applied, following 19 yr of annual applications in continuous winter wheat, Experiment 222.

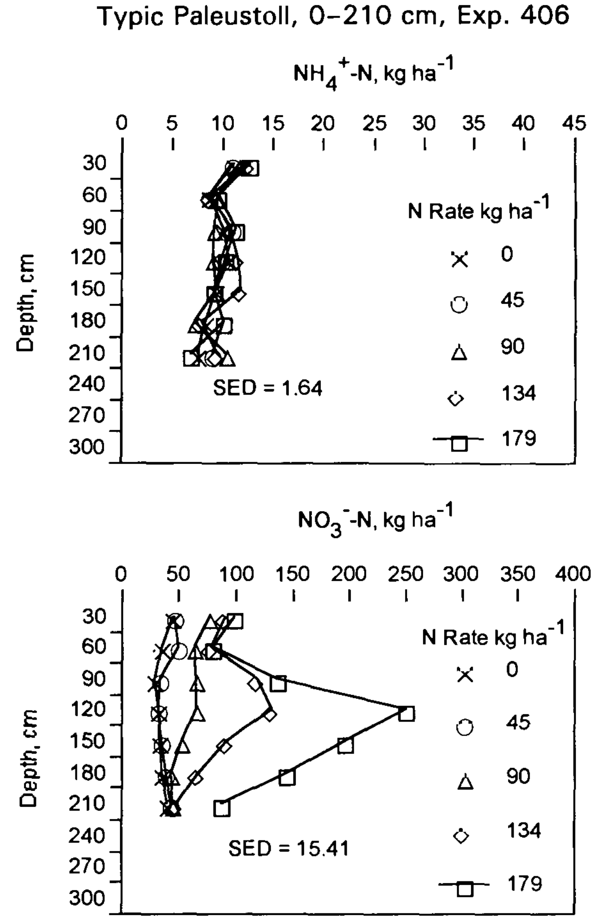

Fig. 2. Soil NH_4^+-N and NO_3^--N in kg ha^{-1} per profile increment as a function of N applied, following 23 yr of annual applications in continuous winter wheat, Experiment 406.

error term from analysis of variance was calculated for NH_4^+-N and NO_3^--N accumulation and grain yield (Table 3 and Fig. 1–4). Approximate statistical significance can be obtained by multiplying SED by 1.96 (*t*-value associated with >120 degrees of freedom); however, significance levels are listed for main effects and contrasts for NH_4^+-N and NO_3^--N accumulation and grain yield data (Tables 4 and 5).

RESULTS AND DISCUSSION

Surface soil (0–15 cm) pH tended to decrease from the time when samples were first taken (1976–1981 depending on the trial) compared with the 1988 sampling (Table 2). An exception was noted in Experiment 222, where pH increased. This apparent increase may be related to the season when samples were taken (9 June 1981 vs. 8 Sept. 1988). All samples (both years included in Table 2) from the other locations were obtained in September.

Grain yield means from the time each experiment was initiated to the time deep soil cores were taken are included in Table 3. Analysis of variance on wheat grain yield for this same time period is reported by location in Table 4. At all locations, grain yield response to N rate was quadratic (Table 4). Averaged across years, no significant grain yield response above N rates of 67 and 90 kg N ha^{-1} (variable rates, depending on experiment) was found at any location (Tables 3 and 4). The significant year × treatment interaction noted at each location is partially explained by the variability in yield response to applied N in different years. In general, yield differences due to N rate were small in drought years and large when moisture was not limiting. Because average grain yields did not increase at N rates in excess of 90 kg ha^{-1}, profile soil N was expected to partially account for the differences in total N applied. Estimates of fertilizer N recovery using the difference method ranged between 40 and 60% at all locations (unpublished data, 1992), which is consistent with that found by Allison (1966).

Analysis of variance for NH_4^+-N and NO_3^--N accumulation in kg ha^{-1} per profile increment (30 cm) is reported by experiment in Table 5, with means shown in Fig. 1–4 for Experiments 222, 406, 502, and 505, respectively. Following more than 18 continuous years of N application, there were no treatment differences in NH_4^+-N accumulation at any depth except in Experiment 505 (Table 5). Accumulation of NH_4^+-N in the soil profile was notably similar at all locations, regardless of N rate (Fig. 1–4). Consistently higher NH_4^+-N levels, especially at the lower depths, were found in the check

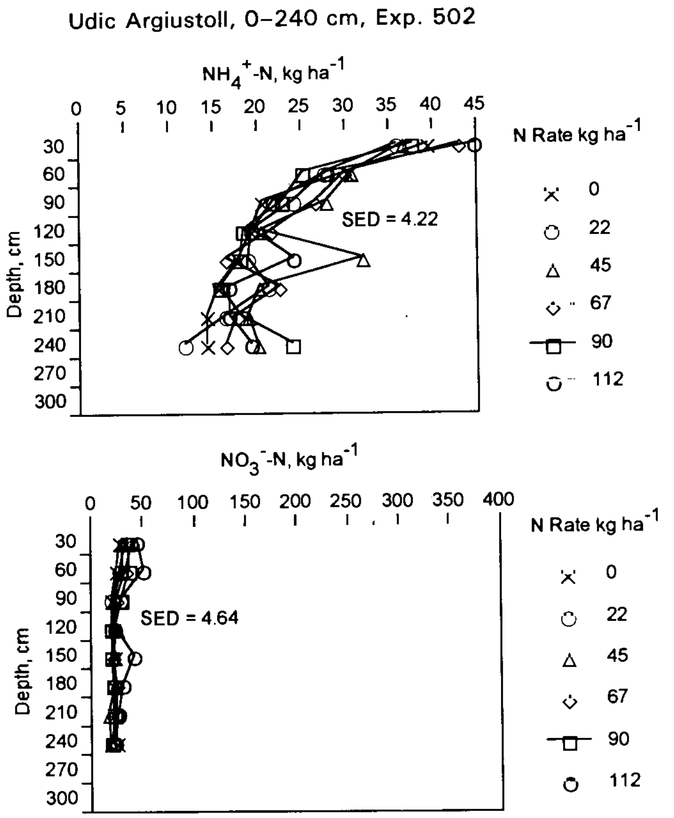

Fig. 3. Soil NH_4^+ –N and NO_3^- –N in kg ha^{-1} per profile increment as a function of N applied, following 18 yr of annual applications in continuous winter wheat, Experiment 502.

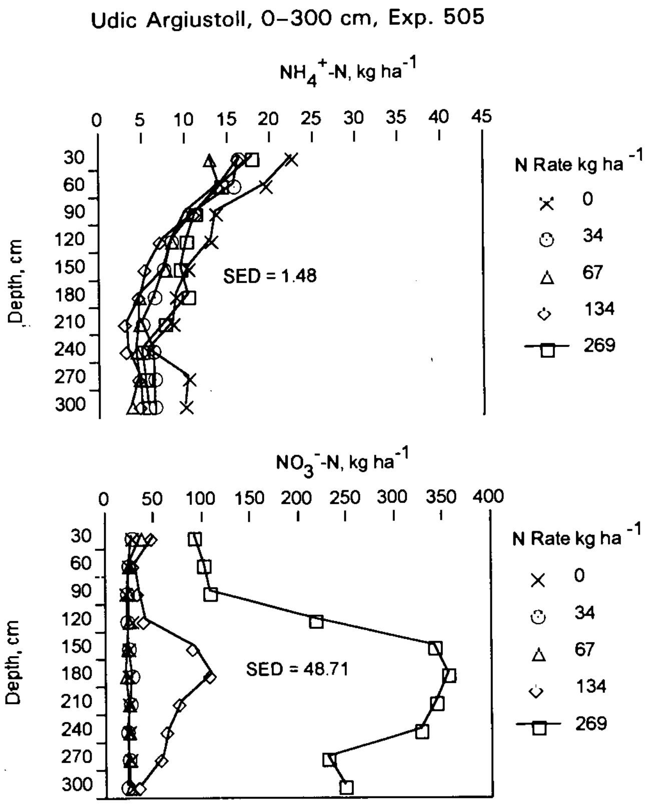

Fig. 4. Soil NH_4^+ –N and NO_3^- –N in kg ha^{-1} per profile increment as a function of N applied, following 20 yr of annual applications in continuous winter wheat, Experiment 505.

Table 4. Split plot in time analysis of variance for wheat grain yield, Mg ha^{-1}, in long-term experiments 222, 406, 502, and 505.

Source of variation†	Grain yield mean squares							
	df	Exp. 222	df	Exp. 406	df	Exp. 502	df	Exp. 505
Rep	3	0.469*	3	0.175	3	0.259	2	0.390
Trt	3	3.464**	4	5.365**	5	8.147**	4	11.688**
N-rate linear	1	8.176**	1	2.995**	1	31.204**	1	30.112**
N-rate quadratic	1	1.974**	1	13.871**	1	8.720**	1	15.998**
Rep × Trt (*a*)	9	0.095	12	0.146	15	0.253	8	0.208
Year	17	9.707**	20	14.764**	16	5.613**	19	4.492**
Year × Trt	51	0.304**	80	0.340**	80	0.591**	76	0.447**
Residual	198	0.083	300	0.103	288	0.074	190	0.088
CV, %		16		17		11		12

*,** Significant at the 0.01 and 0.05 probability levels, respectively.
† Rep, replication; Trt, treatment; *a*, Error *a*.

plots; this was considered to be a function of plot variability in Experiment 505 (Fig. 4).

Although the main effect of treatment on NO_3^-–N accumulation was significant at all locations except Experiment 502, a significant treatment × depth interaction restricted interpretation to simultaneous evaluation of both variables (Table 5). At all locations, no significant differences in NO_3^-–N accumulation were detected at any depth when N rates were $\leq$90 kg N ha^{-1}, as compared with the check plot having received no N fertilization for >18 yr (Fig. 1–4). Nitrogen rates >90 kg N ha^{-1} resulted in significant accumulation of NO_3^-–N in the soil profile (Experiments 406 and 505); the range in detectable differences was less in Experiments 222 and 502 (Fig. 1–4). Because Experiments 502 and 505 were conducted at the same location (183 m apart), this provided an interesting comparison between rates. At the highest N rate employed in Experiment 502 (112 kg N ha^{-1}), NO_3^-–N accumulation was not significantly different from the check where no N was applied (Table 5). At the higher N rates in Experiment 505 (134 and 269 kg N ha^{-1}), marked increases in NO_3^-–N accumulation in the soil profile below 90 cm were found (Table 5 and Fig. 3 and 4). Excess N not consumed by microbial pools, assimilated by the crop, fixed on the exchange complex, denitrified, volatilized and/or immobilized via other pathways was expected to accumulate in subsurface horizons. Also, NO_3^-–N accumulation was expected to occur below 60 cm, where total wheat root volumes are reduced. The decrease in NO_3^-–N back towards background levels at depths >120 cm in Experiments 406 and 505 may have been the result of increased denitrification. Saturated conditions in profiles below the root zone are not uncommon in Experiment 406, where subsurface drainage is intermittently poor.

At Experiments 406 and 502, N rates ≤ 90 kg ha^{-1} maximized grain yields (Table 3). Interestingly, no significant differences in NO_3^-–N accumulation in the soil profile were found at any location when N rates were ≤90 kg ha^{-1}, compared with the check. This could suggest that even liberal N recommendations (33 kg N Mg^{-1} or 2 lb N bushel^{-1}, or approximately 50% more N than

Table 5. Analysis of variance for NH_4^+-N and NO_3^--N in kg ha^{-1}, by depth (30 cm increments).

	Mean squares											
	Exp. 222			Exp. 406			Exp. 502			Exp. 505		
Source of variation†	df	NH_4-N	NO_3-N	df	NH_4-N	NO_3-N	df	NH_4-N	NO_3-N	df	NH_4-N	NO_3-N
Rep	3	387.14*	741.32**	3	10.32	179.38	3	1353.62**	166.86	2	95.25**	2 809.94
Trt	5	118.61	2288.57**	4	4.53	42 063.42**	5	70.28	386.39	4	95.59**	212 230.97**
Rep × Trt (*a*)	15	80.03	112.41	12	7.83	1 341.16	15	71.85	218.58	8	13.11	4 473.21
Depth	9	144.67**	1069.74**	8	119.64**	13 541.64**	9	288.47**	342.70**	11	50.64**	17 847.83**
Trt × Depth	45	4.29	47.89**	32	3.85	4 020.75**	45	32.31	52.78	44	3.62	8 959.98**
Residual	162	4.72	21.72	120	5.40	474.72	162	35.68	43.07	110	3.27	3 559.22
CV, %		15	20		38	31		32	31		23	96

**,* Significant at the 0.01 and 0.05 probability levels, respectively.
† Rep, replication; Trt, treatment; *a*, Error *a*.

that removed in the grain) were consistent with minimizing inorganic N accumulation while also providing maximum grain yields.

Work by Jenny (1941) established that the depth where free $CaCO_3$ was found in midwestern soils was positively correlated with average annual rainfall. Consequently, the presence of free $CaCO_3$ was used as a diagnostic indicator of the average depth of regular wetting in these soil profiles. Free $CaCO_3$ was found at depths of 60, 45, 90 and 90 cm for Experiments 222, 406, 502, and 505, respectively. Although significant amounts of NO_3^--N were found below these depths at all locations, this could

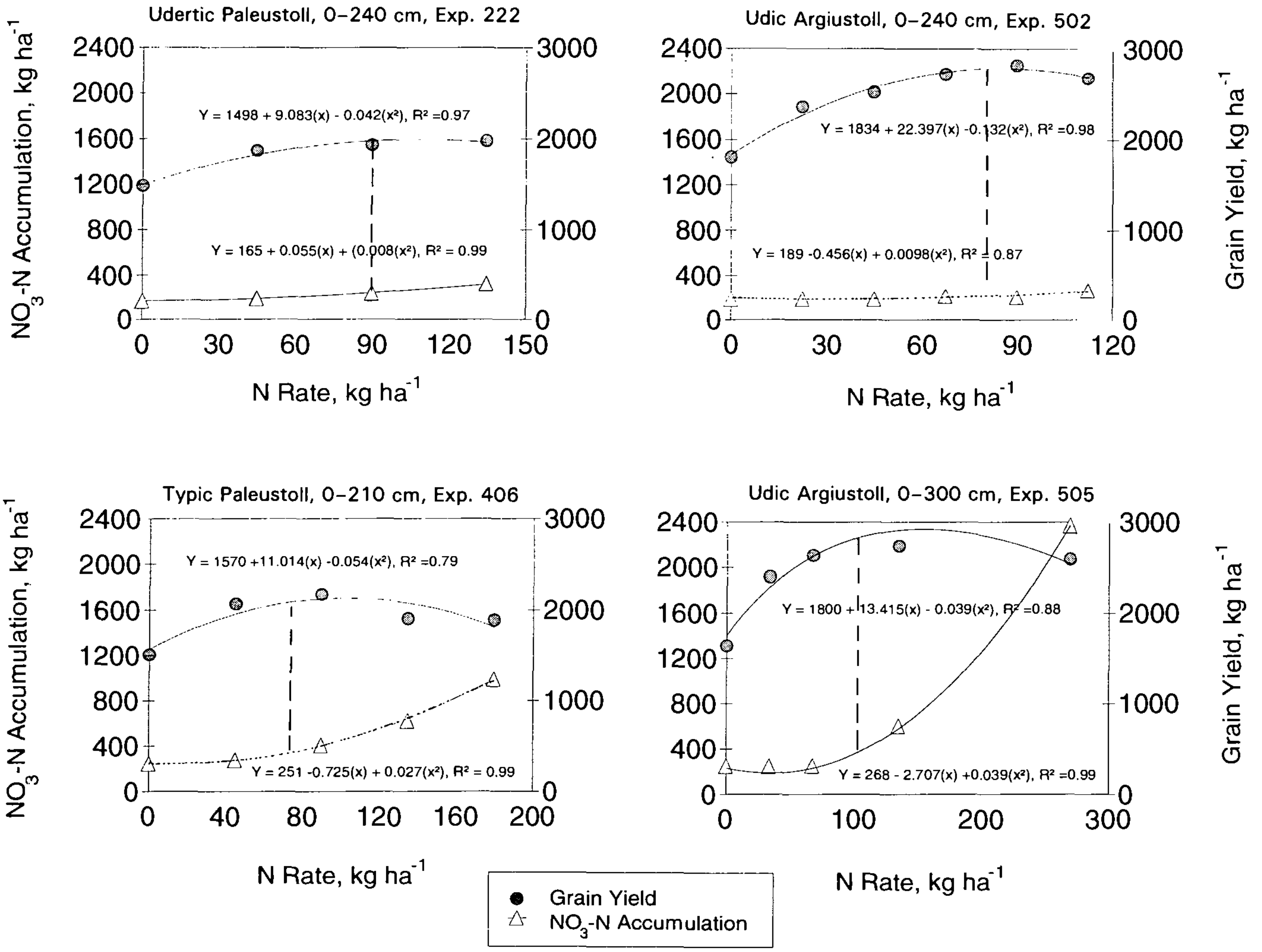

Fig. 5. Quadratic regression equations of average grain yield and total NO_3^--N accumulation in the soil profile over 19, 23, 18, and 20 yr for Experiments 222, 406, 502, and 505, respectively (vertical dashed line represents the point at which the distance between the yield curve and NO_3^--N accumulation curve is maximized).

have been a function of unusual precipitation events over the period of >18 yr included in these studies. However, presence of $CaCO_3$ in the soil profile is an indication that precipitation at these sites does not directly recharge groundwater.

Quadratic regression equations of average grain yield and total NO_3^-–N accumulation in the soil profile over 19, 23, 18, and 20 yr for Experiments 222, 406, 502, and 505, respectively, were generated and plotted accordingly in Fig. 5. In order to determine the point where minimum soil profile NO_3^-–N accumulation corresponded with maximum grain yields (maximum distance between the two curves), the quadratic function for NO_3^-–N accumulation was subtracted from that of grain yield, and the first derivative of that equation was set equal to zero and solved (maximum difference method, both in units of kilograms per hectare). Solutions of this calculation for Experiments 222, 406, 502, and 505 were 90, 73, 80 and 103 kg N ha^{-1}, respectively (vertical dashed line, Fig. 5). These values represent estimates of the N rate that optimized grain yield while simultaneously minimizing the potential for significant soil profile NO_3^-–N accumulation. At all four locations, N rate estimates were equal to or only slightly greater than rates currently recommended to obtain maximum grain yield. Variability in profile NO_3^-–N accumulation and average grain yield as a function of N applied was expected to be small, given that an average of 20 yr of data entered into these estimates.

In general, NO_3^-–N accumulation was not correlated with N applied when N rates were less than or equal to currently recommended rates. Liang et al. (1991) demonstrated that significant amounts of NO_3^-–N accumulated in the soil profile at a high N rate (400 kg N ha^{-1}), compared with recommended rates of 170 kg N ha^{-1} for irrigated corn, over a 3-yr period. Schepers et al. (1991) found that groundwater NO_3^-–N concentrations were positively correlated with residual N in the surface 0.9 m of soil, which reflected past N and water management practices. Their study also concluded that a large portion of average excess N application in irrigated corn was attributed to producers who exceeded the recommended N rate by >100 kg N ha^{-1}. Experimental results reported here corroborate those findings, while further demonstrating that NO_3^-–N accumulation was no different from unfertilized plots when N was applied at the optimum rate for yield. Our results strongly suggest that present N recommendations for continuous winter wheat production provide little risk for potential NO_3^-–N contamination of groundwater. However, these systems represent dryland production where average annual rainfall seldom exceeds 1000 mm yr^{-1}. Therefore, it is likely that results may differ for other crops managed under irrigation and on more freely drained, deep sandy soils.

Total N loading over time in these experiments differs from that used by farmers in fields under continuous wheat production. These experiments annually received the same N rates, disregarding the amount of residual N present in the profile. Alternatively, farmer N rates are normally based on a specific yield goal and soil test N, whereby actual rates used in a given year are reduced according to residual soil N. Furthermore, N rates for optimum economic yield are expected to be somewhat less than those required for long-term maximum grain yield. In this regard, average farmer N rates for the same time period used in this study would have been much less than that needed to significantly increase soil profile NO_3^-–N accumulation.

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