Nitrate leaching as influenced by fertilization in the Brown soil zone

C. A. Campbell, R. P. Zentner, F. Selles, and O. O. Akinremi

Research Station, Research Branch, Agriculture Canada, Swift Current, Saskatchewan, Canada S9H 3X2. *Received 29 Jan. 1993, accepted 31 May 1993.*

Campbell, C. A., Zentner, R. P., Selles, F. and Akinremi, O. O. 1993. **Nitrate leaching as influenced by fertilization in the Brown soil zone.** Can. J. Soil Sci. **73**: 387-397. The possibility of nitrates being leached into groundwater supplies from improper use of fertilizers is a concern to society. Two experiments were conducted on a loam soil in the Brown soil zone at Swift Current, Saskatchewan. In the first experiment, continuous wheat (*Triticum aestivum* L.), grown under various fertilizer-N management systems and with and without cereal trap strips (tall stubble, 0.4–0.6 m) to capture snow and enhance soil-moisture storage, was compared with short stubble cut at the standard height (0.15–0.2 m). Prior to seeding in spring 1991, tall stubble had stored 14.7 ha–cm of soil moisture at 0–1.2-m depth compared with 10.9 ha–cm under short-stubble treatment. Because growing-season precipitation in 1991 was much higher than normal (302 mm from 1 May to 31 July), considerable NO_3-N was leached below the rooting zone of wheat (1.2 m), particularly in the tall-stubble treatment. Leaching patterns were as expected in short stubble, with major leaching occurring only at the highest N rate (125 kg ha^{-1}), where yield and N-uptake response had levelled off. However, in tall stubble, the amount of NO_3-N leached beyond the root zone under the 0 and 25 kg N ha^{-1} rates was similar to that under the 125 kg N ha^{-1} rate. This result was attributed to poor tillering obtained at low N rates, which contributed to lower evapotranspiration, thereby permitting more moisture to be leached and enhancing N mineralization. When we used a leaching model (NLEAP) to simulate our results, it gave lower estimates of NO_3 leached and did not reveal the interaction of NO_3-N leaching with N rates that was observed under tall stubble. The second experiment measured soil NO_3-N distribution to 2.4 m under two fallow–wheat–wheat systems after a 24-yr period. One system received only N, the other, N + P fertilizer. The results corroborated those obtained under tall stubble in the first experiment: the poorly fertilized system had the most NO_3-N below the root zone. The results of this study suggest that the key to reducing nitrate leaching is the adoption of proper fertilization practices, since too little fertilization may potentially be as detrimental to groundwater pollution as too much.

Key words: Fertilizer N, N uptake, snow management, crop rotations, NO_3 leaching

Campbell, C. A., Zentner, R. P., Selles, F. et Akinremi, O. O. 1993. **Lessivage des nitrates selon le régime de fumure dans la zone des sols bruns.** Can. J. Soil Sci. **73**: 387-397. Les risques d'entraînement des nitrates dans les réserves d'eau souterraine, par suite de l'usage inconsidéré des engrais, inquiètent la société. Deux expériences ont été réalisées dans un loam de la zone des sols bruns à Swift Current, Saskatchewan. Dans la première, on comparait la culture du blé en continu (*Triticum aestivum* L.) sous divers régimes de fumure N, avec et sans bandes de chaume coupé haut (0,4–0,6 m) pour garder la neige et ainsi accroître les réserves d'eau du sol, avec du blé coupé à la hauteur normale (0,15–0,2). Par comparaison avec la récolte en chaume court, les bandes de chaume capte-neige avaient permis de stocker, avant le semis de printemps 1991, 14,7 ha–cm d'eau du sol dans la tranche de 0 à 1,2 m de profondeur, contre 10,9 ha–cm en régime de récolte avec chaume court. Comme la saison de végétation 1991 était beaucoup plus pluvieuse que la normale (302 mm du 1er mai au 31 juillet), une quantité considérable de N nitrique était entraînée en dessous de la rhizosphère du blé (1,2 m), surtout dans le traitement sous chaume court. Les courbes du lessivage observées sous chaume court concordaient avec ce qu'on attendait, le lessivage n'atteignant des proportions importantes qu'au taux de fumure N le plus élevé (125 kg ha^{-1}), auquel le rendement et l'absorption de N avaient atteint un plafond.

En revanche, dans les parcelles sous chaume long, les quantités de N entraînées au-delà de la rhizosphère aux doses de fumure 0 et 25 kg N ha^{-1} étaient les mêmes qu'à la dose de 125 kg. Le tallage abondant obtenu aux doses de fumure inférieures et la moindre évapotranspiration qui en résultait permettrait à plus d'eau d'être entraînée, en plus de stimuler la minéralisation de N. Le recours à un modèle de percolation (NLEAP) pour simuler nos résultats nous a fourni des valeurs de lessivage de NO_3 plus basses. Par ailleurs, nous n'avons pas observé l'interaction entre les quantités de N nitrique lessivées et le taux de fumure N que nous avions observée sous chaume long. Dans la deuxième expérience, la répartition de N nitrique dans le sol était mesurée jusqu'à la profondeur de 2,4 m, dans deux assolements jachère–blé–blé, au bout d'un cycle de 24 ans. Un des assolements ne recevait que du N, l'autre recevant à la fois N et P. Les résultats confortent ceux observés dans les parcelles sous chaume long dans la première expérience, en cela que c'est l'assolement le moins richement fertilisé qui montrait la plus de N nitrique au-delà de la rhizosphère. Les résultats de cette étude portent à conclure que la clef de la diminution du lessivage des nitrates réside dans l'adoption de bonnes pratiques de fumure: trop peu d'engrais pourrait contribuer autant à la pollution des eaux souterraines qu'une fumure excessive.

Mots clés: N de fumure, absorption de N, conservation de la neige, rotation des cultures, lessivage de NO_3

Society is concerned with possible negative impacts of agricultural practices, especially fertilizers, on soil and water quality (Follett 1989; Germon 1989; Addiscott et al. 1991). Nitrate leaching in soils depends on such factors as texture, N uptake by plants, fertilizer inputs, precipitation, drainage and N-transforming processes as mineralization, immobilization and denitrification (Linville and Smith 1971; Hedlin and Cho 1974; Follette 1989). Generally, NO_3-N may be leached from a system if available soil N exceeds plant needs, especially if this occurs when there are no growing plants to use the N before excess water moves it beyond the root zone (Follett 1989).

Because the Canadian Prairie is characterized by high moisture deficits, it is often assumed that NO_3 leaching is unlikely to occur. However, Campbell et al. (1984) demonstrated that, in years with above-average precipitation, significant amounts of NO_3-N can be leached beyond the rooting zone of cereals even in the Brown soil zone at Swift Current, Saskatchewan, where the annual moisture deficit (potential evapotranspiration minus precipitation) is 395 mm. These authors showed that although leaching was much greater when land was summerfallowed frequently, leaching could also occur on land that was cropped annually. They also showed, contrary to common belief, that systems that had been underfertilized permitted more NO_3 leaching than those that were properly fertilized. Similar results were reported for a 30-yr irrigated-maize study, where inadequate P application resulted in greater NO_3-N accumulation below the root zone than when both N and P were adequately supplied (Schlegel and Dhuyvetter 1992).

In 1991, growing-season (1 May to 31 July) precipitation in the Swift Current area was almost twice the long-term average of 167 mm. A 10-yr study involving snow trapping and fertilizer-N management for continuous wheat (*Triticum aestivum* L.) grown under zero tillage management allowed us to assess NO_3 leaching under these various conditions. As well, deep cores were taken in summer 1990 from a long-term crop-rotation experiment conducted on the same soil type at the Swift Current Research Station and previously described by Campbell et al. (1984). This allowed us to reassess our earlier observations on the influence of inadequate P fertilization on NO_3 leaching.

The objectives of this study were (1) to determine the influence of fertilizer-N rate and the long-term impact of under-fertilization with P on NO_3 leached under hard red spring wheat systems in the Brown soil zone and (2) to relate NO_3 leaching to N uptake by the crop.

MATERIALS AND METHODS

Experiment 1: Snow × Fertilizer-N Management of Spring Wheat

This ongoing experiment was initiated in spring of 1981 on farm land near Swift Current, Saskatchewan. Prior to our study, the farmer grew spring wheat with fallow once every 2 or 3 yr. Details of layout, plot dimensions and treatments to 1990 have been presented elsewhere (Campbell et al. 1986, 1992, 1993a,b). The soil is a Swinton loam (Ayres et al. 1985), an Orthic Brown Chernozem. The experimental design was a randomized complete block with split-plot treatments. There were four 2.5-ha replicates. The main plots were two stubble-height treatments: a uniform short stubble, cut 0.15–0.2 m high to represent the conventional farming practice; and a tall–short (tall part = 0.4–0.6 m) stubble (hereafter called tall stubble), constructed at harvest (Campbell et al. 1992). The tall-stubble strips were established in a north–south direction, perpendicular to prevailing westerly winds, to facilitate snow trapping.

The main plots were divided into three equal areas that allowed the experiment to be moved each year to minimize residual effects of fertilizer. During the first 9-yr period ending in 1990, the experiment involved several combinations of N and P rates, N placement (deep banded vs. broadcast) and time of N application (fall vs. spring) (Campbell et al. 1986, 1992, 1993a,b). In 1991, we changed the experiment by replacing the time-of-N-application treatments with a zero-till vs. preseeding-tillage treatment. Furthermore, all P treatments were omitted, and six N rates were used (0, 25, 50, 75, 100 and 125 kg N ha^{-1}). The N was applied as urea in spring, about 1 wk prior to tillage and seeding. Phosphorus was applied (seed-placed) as triple superphosphate at 13 kg P ha^{-1} to all treatments. All fertilizer treatments were randomized in the test plots each year.

The plots were seeded on 24 May 1991 at a rate of 67 kg ha^{-1} to hard red spring wheat cv. Leader, using a zero-till offset disk drill (Dyck and Tessier 1986) at 17.8-cm row spacing. Herbicides were applied as required for satisfactory weed control: 2,4-D ester in the fall, occasional bromoxynil plus glyphosate pre-emergence, bromoxynil plus MCPA and (or) diclofop methyl, post-emergence. A small-plot combine was used to take two grain samples at harvest (7 September in 1991). The area of each sample was 12.7 m × 1.2 m and was taken at right angles to the trap strips and the direction of seeding. At harvest, a 1-m row of plants was taken from each plot and used to determine straw/grain ratio, heads per plant, and N concentration (Kjeldahl) of straw. All plant material was dried at 70°C overnight, weighed, ground and used for determination of N concentration. The straw/grain ratios were used, together with combine grain yields, to calculate straw yields (kilograms per hectare).

On 4 October 1990 and 8 May 1991, a Giddings soil corer was used to sample soil to a depth of 1.2 m for moisture content (gravimetric) and for NO_3-N concentration (Hamm et al. 1970) at the same position in each replicate. Because the 1991 growing season was wet (302 mm precipitation received from 1 May to 31 July, compared with long-term mean of 167 mm for this region), we again sampled the plots immediately after harvest (19–21 September). Samples were taken at 0.3-m increments to a depth of 2.4 m in each treatment for determination of moisture, NO_3-N and bulk densities. The bulk densities for eight successive 0.3-m layers of this soil were 1.27, 1.39, 1.54, 1.69, 1.76, 1.75, 1.78 and 1.77 Mg m^{-3}, respectively. We used the bulk densities to convert gravimetric moisture (percentage by weight) to volumetric units (hectare–centimetres) and to convert NO_3-N concentrations (percentages) to kilograms per hectare.

Experiment 2: Effect of Fertilizer P on NO_3 Leaching on Fallow–Wheat–Wheat in a Long-term Rotation

The long-term rotation study at Swift Current has been extensively reported in the literature (Campbell et al. 1984; Zentner and Campbell 1988); therefore, only a brief description of this system is presented here.

Two of 12 crop rotations established at Swift Current in 1967 on a Swinton loam (Ayres et al. 1985) were used for this study. Both systems were fallow–wheat–wheat (F–W–W), one receiving N + P fertilizer and one receiving only N. The N was applied at soil-test-recommended rates, but P was applied at the generally recommended rate for wheat grown on this soil (Saskatchewan Agriculture, Soils and Crop Branch, 1988). Phosphorus, as monoammonium phosphate (11-48-0), was seed-placed; N, as ammonium nitrate (34-0-0), was broadcast and incorporated with a preseeding tillage. During the 1967–1990 period, F–W–W (N + P) received an average of 11.2 kg N ha^{-1} yr^{-1} and 6.2 kg P ha^{-1} yr^{-1}, while F–W–W (N) received 6.2 kg N ha^{-1} yr^{-1}. Treatments were arranged in a randomized complete-block design with three replicates. All phases (rotation–year) of each rotation were present each year (i.e., nine plots for each rotation), and each rotation was cycled on its assigned plots.

On 31 July 1990, a Giddings soil corer was used to take soil samples to a depth of 3 m in the fallow phase of each rotation. Soil-moisture content, NO_3-N, and bulk densities were measured on each 0.3-m layer, as discussed in exp. 1. Bulk densities for successive 0.3-m layers of this soil were 1.29, 1.30, 1.50, 1.59, 1.64, 1.64, 1.67, 1.78, 1.73 and 1.68 Mg m^{-3}, respectively.

Statistical Analysis

In exp. 1, NO_3-N and soil moisture were initially analyzed as a split-split-split-split plot, with stubble height as main plots and tillage, fertilizer rate, N placement and depth as successive subplots. Because tillage and N placement had no significant effect and their interactions were not significant ($P > 0.05$), we pooled these data as replicates and reanalyzed the data as a split-split plot, with stubble height as main plot, fertilizer-N rate as subplot, and depth as sub-subplot. We also determined the NO_3-N located between 1.2 and 2.4 m and analyzed this as a split plot, with stubble height as main plot and N-fertilizer rate as subplot (16 replicates) (Little and Hills 1978). Grain yields and N content (percentage N × yield) of grain and straw were analyzed also as a split plot. Multiple-regression techniques were used to relate grain yield and plant (above-ground) N to rate of fertilizer N.

In exp. 2, soil NO_3-N and soil moisture were analyzed as a split plot, with rotation as main plot and depth as subplot. In all cases, LSD values ($P = 0.10$) were calculated for comparing significant ($P < 0.05$) treatment means (Little and Hills 1978).

RESULTS AND DISCUSSION

Effect of Snow Management and Rate of Fertilizer N

A fairly dry autumn in 1990 allowed high overwinter soil-moisture recharge (Campbell et al. 1992); consequently, tall stubble had 147 mm of available moisture (i.e., moisture held by soil at potentials above 4 MPa: Cutforth et al. 1991) in the 0–1.2-m layer when sampled on 7 May, while short-stubble treatments had 109 mm (Table 1). In a dry or average year, this difference in stored moisture would have resulted in a significant yield increase favoring tall stubble (Campbell et al. 1992). However, in the wet growing season of 1991 (Table 1) there was no effect of stubble height on grain (Fig. 1) or straw yields (data not shown).

Grain-yield response to fertilizer-N rate followed the classic quadratic model, increasing steeply in response to rate up to 75–100 kg N ha^{-1}, then levelling off (Fig. 1). However,

Table 1. Available moisture in spring and growing-season precipitation for the experimental period (exp. 1)

	Available moisture in 0–1.2-m layer in spring (mm)[z]		Growing-season precipitation (mm)[y]				Total available moisture in growing season (mm)	
Crop year	Tall stubble[x]	Short stubble[x]	May	June	July	Total	Tall stubble[x]	Short stubble
1982	38	28	82	43	119	244	282	272
1983	111	93	62	29	96	187	298	280
1984	58	42	18	67	15	100	158	142
1985	82	56	31	17	25	73	155	129
1986	39	33	122	51	32	205	244	238
1987	83	80	26	44	59	129	212	209
1988	23	10	35	73	35	143	166	153
1989	37	29	61	118	31	210	247	239
1990	63	58	50	43	86	179	242	237
1991	147	109	96	164	42	302	449	411

[z] Available moisture is moisture held by soil at potentials above - 4 MPa; at −4 MPa this soil retains 154 mm of moisture in the 0–1.2-m layer.

[y] The long-term (102-yr) mean = 165 mm.

[x] Tall stubble refers to the tall-short treatment constructed at harvest in which one strip of stubble stands 0.4–0.6 m tall by 0.3 m wide every 6 m, with the remainder of the 6-m area being short (0.15–0.2 m); short stubble was cut at 0.15–0.2 m height.

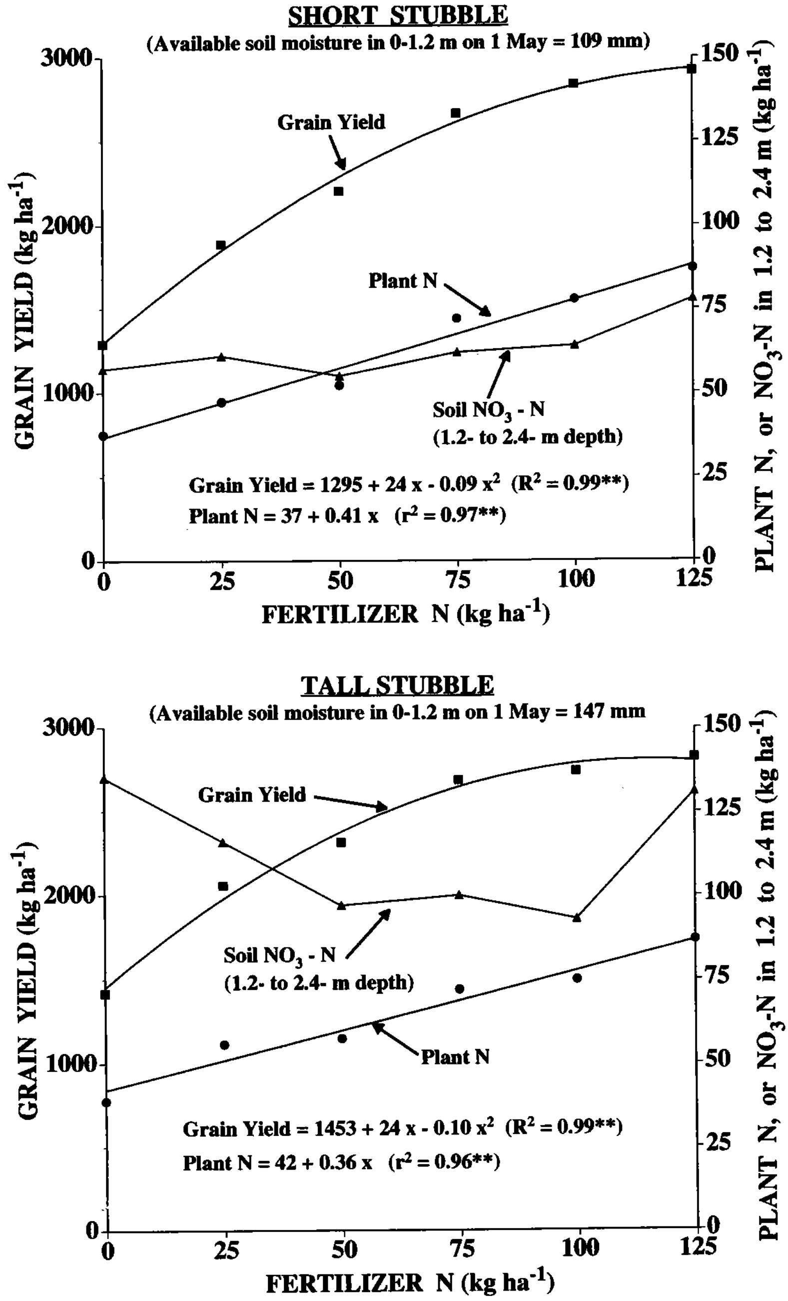

Fig. 1. Interrelationship between grain yield, above-ground plant N, and leached NO_3-N as influenced by rate of fertilizer N and spring soil moisture in a wet year at Swift Current, Saskatchewan: (top) short-stubble treatment; (bottom) tall-stubble treatment. (Between 1 May and 31 July 1991, 302 mm of precipitation was received.) For subsoil NO_3-N (1.2–2.4 m), the LSD ($P < 0.05$) for the interaction (stubble height × N rate) means = 25 kg ha^{-1}.

above-ground plant N was linearly related to rate of N applied, and the maximum was beyond the N rates used in this experiment.

Variance analysis showed a significant effect of stubble height, N rate, and height × N rate interaction on subsoil NO_3-N after harvest 1991. There was significantly less ($P < 0.05$) NO_3-N below the root zone of wheat under the short-stubble treatment (Fig. 1, top) than under the tall-stubble treatment (Fig. 1, bottom), even though N uptake was similar for the two systems. Unfortunately, we did not measure NO_3-N distribution in the subsoil prior to seeding. However, this land was continuously cropped for the previous 9 yr, and in that period the plots would only have been test plots for 3 yr, so N rates would have been only 25 kg ha^{-1} in the other 6 yr. During the experimental period, 4 yr (1984, 1985, 1987 and 1988) had well below-average growing-season precipitation, and, further, spring soil moisture in these years was low (Table 1). In the other 6 yr of above-average growing-season precipitation, only 1983 and 1991 had high spring soil moisture. In 1983, most of the growing-season precipitation came in July, when the soil would have already been dried out by the crop; therefore, leaching would have been minimal in that year. It was only in 1991 that very high spring soil moisture was accompanied by an extremely wet May and June (early June). In 1991 the crop was seeded on 24 May; thus, it had not grown very much when most of the precipitation was received. Although 1989 and 1990 were wet years, above-average crops (Campbell et al. 1992) led to high N uptake (Campbell et al. 1993a); thus, residual N would be small thereafter, as shown by Campbell and Paul (1978). Based on this evidence, it seems reasonable to assume that subsoil nitrate levels were low in this experiment prior to fertilization in spring 1991.

The results (Fig. 1) suggest that, because of the extra 38 mm of soil moisture present under tall stubble in spring 1991, (i) more NO_3-N may have been mineralized in this system; (ii) more NO_3-N may have been leached from the tall-stubble system during the growing season; and (iii) most of the leaching of NO_3-N would have occurred early (May–June), before the crop could use a major portion of the applied and mineralized N.

Evidence of NO_3-N leaching, particularly under tall stubble, was confirmed by the NO_3-N accumulations below the rooting zone (1.2 m) of wheat (Fig. 2). The NO_3-N distribution in the short-stubble treatment was as anticipated; for example, there was a low amount of NO_3-N below the root zone of wheat, except at the highest N rate, where fertilizer N was probably in excess of plant requirements (Fig. 1, top). These results are similar to those reported by McMahon (1988). Results in the tall-stubble treatment were somewhat surprising because here NO_3 leaching was as high in the zero-N and 25 kg N ha^{-1} treatments as in the 125 kg N ha^{-1} treatment (Fig. 2, bottom).

The high NO_3-N leached at low N rates was likely associated with very low tillering (data not shown) that was obtained at 0 and 25 kg N ha^{-1}. First, the low tillering at low N rates resulted in less evapotranspiration compared with that at higher N rates (Fig. 3), thereby allowing more water to pass beyond the root zone especially early in the growing season. This extra moisture must have passed beyond 2.4 m because it was not reflected in subsoil at harvest (Fig. 3). Second, the moist conditions at the lower N rates may have allowed greater N mineralization to take place in these treatments. Third, the much higher initial soil moisture under tall stubble than under short stubble would tend to exacerbate these conditions. Although there was no difference in soil-moisture content between tall- and short-stubble treatments at harvest (Fig. 3), there was a difference in spring (Table 1); thus, the excess moisture under tall stubble must have drained beyond 2.4 m. Further, the movement of nitrate and moisture must not have coincided in this zero-tilled soil.

Estimating NO_3 Leaching with NLEAP

Because the amount of NO_3 leached beyond the rooting zone was not measured directly in

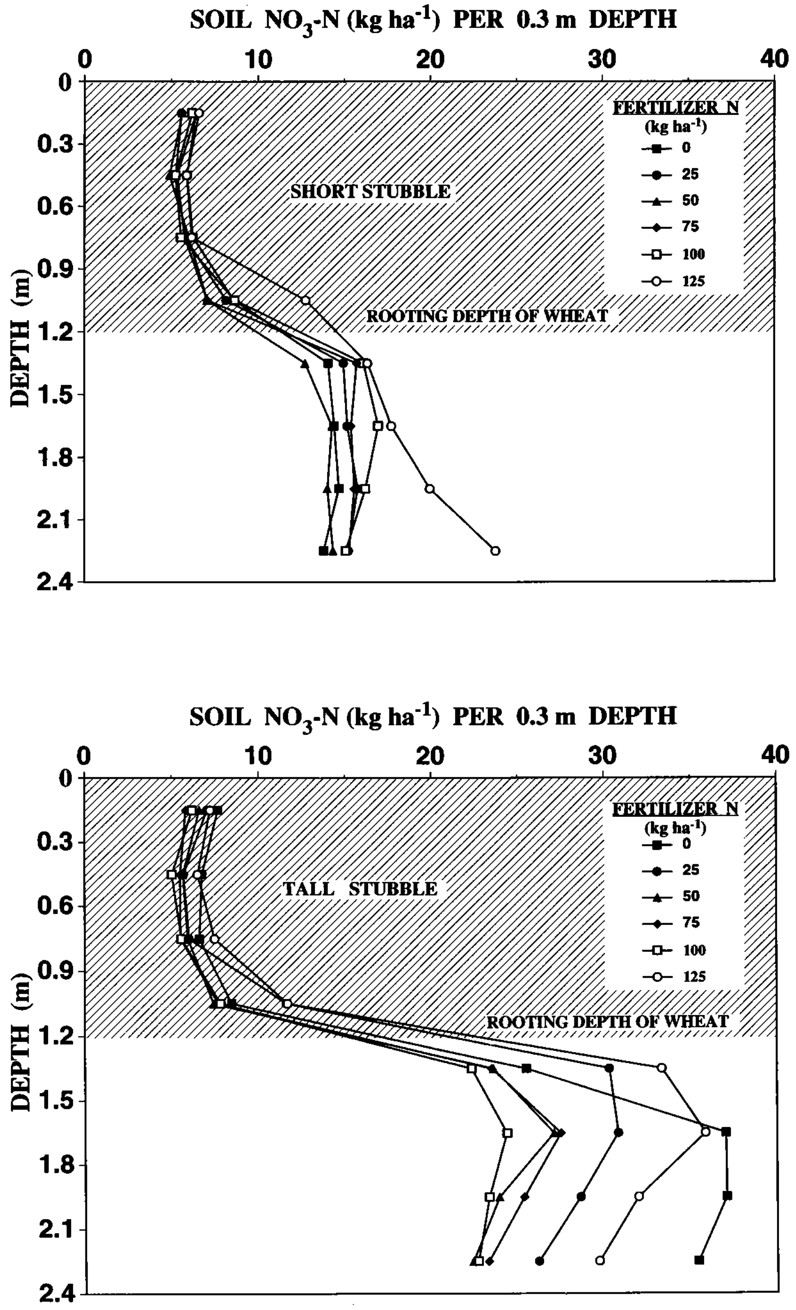

Fig. 2. Interaction of stored soil moisture and rate of fertilizer N on NO_3-N distribution in the soil profile: (top) short-stubble treatment; (bottom) tall-stubble treatment. (Sampled immediately after harvest in 1991.)

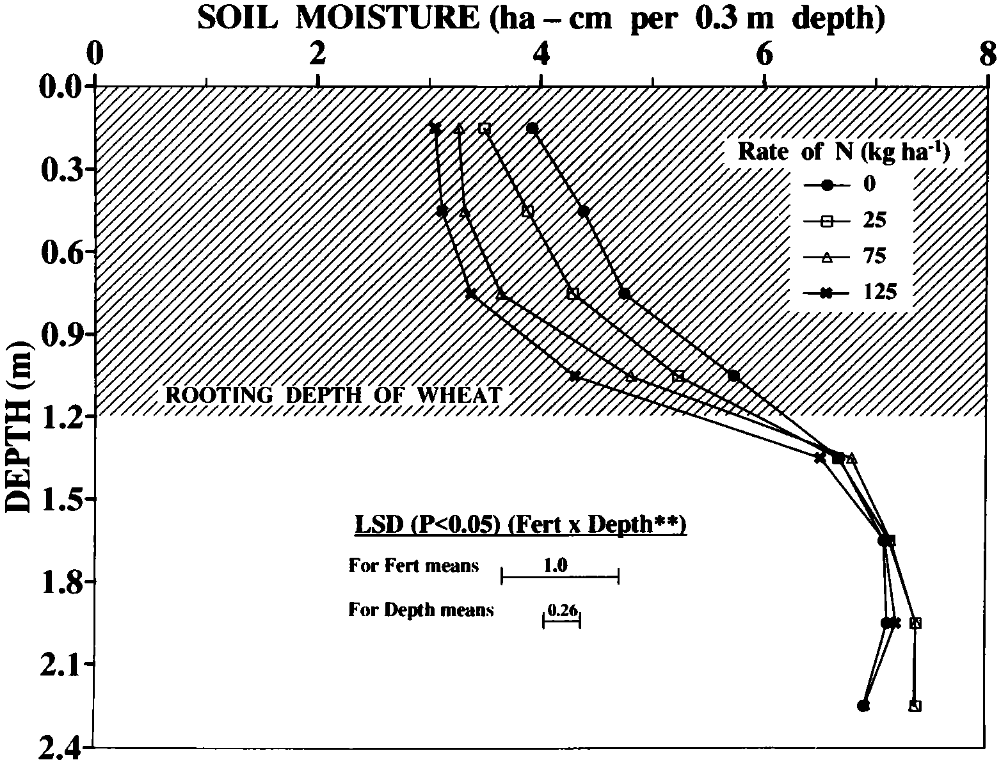

Fig. 3. Soil-moisture distribution in soil profile immediately after harvest 1991 as influenced by fertilizer-N rate. The fertilizer × depth interaction was significant ($P < 0.001$), but stubble height was not; therefore, values were averaged over stubble height.

this experiment, we used the NLEAP model (Follett et al. 1991) to estimate the amount of leaching in 1991. NLEAP is a management model designed to provide a rapid, site-specific estimate of NO_3-N leaching potential under agricultural crops. The model was initialized using the NO_3-N levels measured in the fall of 1990 together with the moisture content measured in the spring of 1991. The amounts of NO_3-N in the soil in fall 1990 were 5.64, 4.81, 5.61, and 10.41 kg ha^{-1} at depths of 0–0.3, 0.3–0.6, 0.6–0.9, and 0.9–1.2 m, totalling 26.47 for the 0–1.2-m layer. Soil-moisture volumetric units on 8 May 1991 in the respective depth intervals under short stubble were 8.4, 7.7, 5.9 and 4.5 ha-cm, for a total of 26.5 ha-cm; in tall stubble, the respective values were 8.6, 7.8, 7.0 and 6.7 ha-cm, for a total of 30.1 ha-cm. The driving variables (used to run the model) included the daily precipitation, the monthly pan evaporation and the mean monthly air temperature. The fertilizer and crop management information were obtained from the experimental data. The yields obtained in 1991 were used as expected yield.

Based on our calculations with NLEAP, 15.2 ha-cm of water should have leached beyond 1.2 m in the tall-stubble treatment in 1991, and 12.7 ha-cm should have leached from the short-stubble treatment. According to the model, this amount would not vary with rate of N, but we question this aspect of the model and suggest that, as shown in our results (Fig. 3), the rate and amount of moisture used by the crop are directly related to rate of N (Campbell et al. 1977), and therefore the amount of moisture available for leaching should be inversely related to rate of N. The calculations with NLEAP indicated that the amount of NO_3-N leached would increase in direct proportion to N rate and be greater under tall than under short stubble. Predicted NO_3-N leached under short stubble fertilized at 0, 25, 50, 75, 100 and 125 kg N ha^{-1} were 19, 20, 22, 22, 24 and 25 kg ha^{-1}; and under tall stubble, 21, 22, 25, 26, 28 and 28 kg ha^{-1}, respectively. These results are lower in absolute amounts than we measured, but since we had no initial values beyond 1.2 m in spring 1991, we cannot be certain which situation is correct. However, in some studies it has been shown that zero tillage can facilitate NO_3 leaching quite markedly because of its effect on porosity (Phillips et al. 1980; Thomas et al. 1973). NLEAP does not take this factor into account. The model predicted the trends in NO_3-N leaching that we observed for stubble-height effects, and the trend with respect to the effect of the rate of N was generally correct. However, NLEAP did not elucidate the interaction we observed with respect to N rate and NO_3-N leached under tall stubble. Obviously, there are some important mechanisms of NO_3 leaching that are still to be accounted for in models such as NLEAP.

Effect of Fertilizer N in a F–W–W Long-term Rotation

As found in 1982 (Campbell et al. 1984), the NO_3-N content below the root zone (1.2–3.0 m) in 1990 was significantly ($P < 0.10$) greater in several depth intervals under the F–W–W (N) system that had not received P fertilizer during the previous 24 yr than under F–W–W (N + P) (Fig. 4). Our

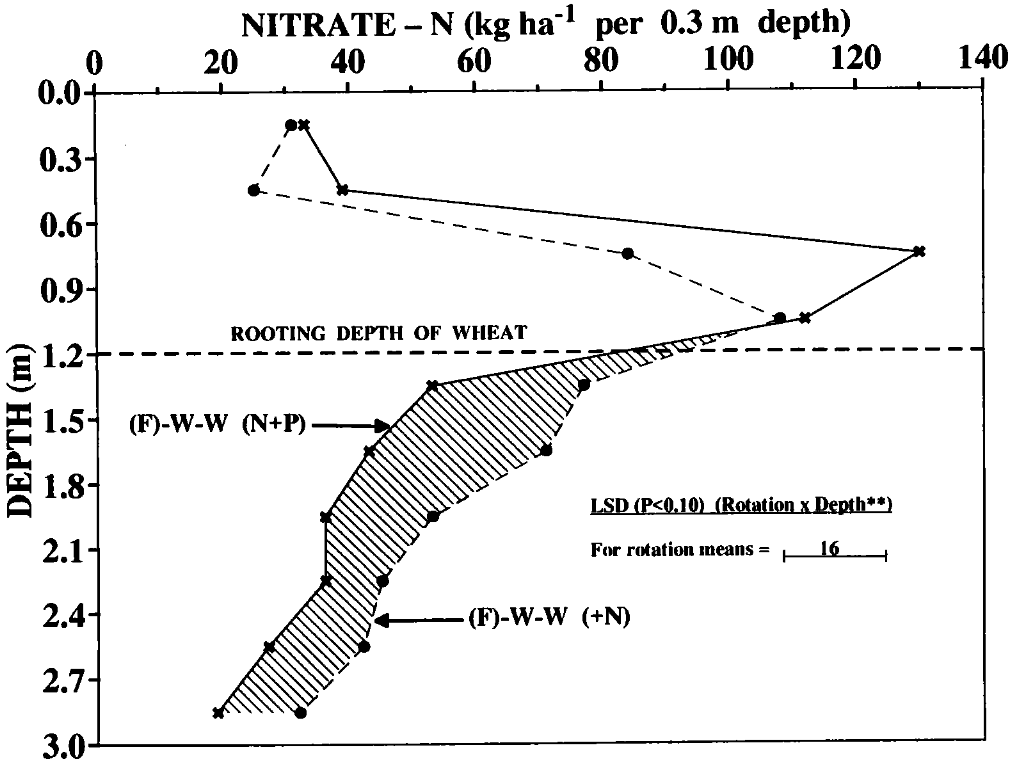

Fig. 4. Effect of withholding fertilizer P on NO_3-N distribution in the soil profile under fallow–wheat–wheat (F–W–W) at Swift Current after 24 yr. (The fallow phase was sampled on 31 July 1990.)

calculations (Campbell and Zentner 1993) showed that in the 24-yr period, the F-W-W (N + P) system received 120 kg ha^{-1} more N than F-W-W (N) (i.e., 270 vs. 150 kg ha^{-1}). But, over the same period, F-W-W (N + P) only exported (in grain) 78 kg N ha^{-1} more than F-W-W (N) (i.e., 739 vs. 661 kg ha^{-1}). Thus, an apparent N balance would suggest that the F-W-W (N + P) should have had about 42 kg ha^{-1} more N available for leaching than the F-W-W (N) system. In fact, we found more NO_3-N leached from the poorly fertilized system over the years (321 vs. 214 kg ha^{-1}). These results support earlier observations (Campbell et al. 1984) and corroborate the findings of Schlegel and Dhuyvetter (1992). It is likely that these findings are related to the consistently reduced plant production of the inadequately fertilized system (Zentner and Campbell 1988) and the reasons suggested with respect to the similar results obtained in exp. 1.

CONCLUSIONS

The results of this study show that, in the infrequent years when growing-season precipitation is well above average in southwestern Saskatchewan, considerable amounts of NO_3-N may be leached below the rooting zone of spring wheat. Our results corroborated evidence in the literature that if mineral N is in excess of plant requirements under wet conditions, NO_3-N will easily leach beyond the root zone of cereals. The most surprising finding in our study was that NO_3 leaching from treatments that were inadequately fertilized could be as great as that from systems receiving excess fertilizer N. We suggested that the latter was due to poor plant growth (and restricted tillering) at low fertility, resulting in low evapotranspiration and thereby leaving more soil moisture available for inducing net N mineralization and inducing greater NO_3-N leaching. This observation may need to be considered in the development of models of nitrate leaching. The key to reducing NO_3-N leaching is proper fertilization (not too much or too little), which can best be determined by using soil-test criteria as a guide.

ACKNOWLEDGMENTS

The authors wish to thank Darrell Hahn, Barry Blomert, Gary Winkleman, Rod Ljunggren, Del Jensen, Don Reimer and Dean James for technical assistance. We also wish to thank WestCo Fertilizer for its financial assistance.

Addiscott, T. M., Whitmore, A. P. and Powlson, D. S. 1991. Farming, fertilizers and the nitrate problem. CAB International, Wallingford, U.K.

Ayres, K. W., Acton, D. F. and Ellis J. G. 1985. The soils of the Swift Current map area 72J, Saskatchewan Institute of Pedology, Publ. 86. Distributed by Extension Division, University of Saskatchewan, Saskatoon, SK, Extension Publ. 481.

Campbell, C. A. and Paul, E. A. 1978. Effects of fertilizer N and soil moisture on mineralization, N recovery and A-values, under spring wheat grown in small lysimeters. Can. J. Soil Sci. **58**: 39-51.

Campbell, C. A., and Zentner, R. P. 1993. Soil organic matter as influenced by crop rotations and fertilization in an Aridic Haploboroll. Soil Sci. Soc. Am. J. **57**: 1034-1040.

Campbell, C. A., Cameron, D. R., Nicholaichuk, W. and Davidson, H. R. 1977. Effects of fertilizer N and soil moisture on growth, N content, and moisture use by spring wheat. Can. J. Soil Sci. **57**: 289-310.

Campbell, C. A., De Jong, R. and Zentner, R. P. 1984. Effect of cropping, summerfallow and fertilizer nitrogen on nitrate-nitrogen lost by leaching on a Brown Chernozemic loam. Can. J. Soil Sci. **64**: 61-74.

Campbell, C. A., Nicholaichuk, W., Zentner, R. P. and Beaton, J. D. 1986. Snow and fertilizer management for continuous zero-till spring wheat. Can. J. Plant Sci. **66**: 535-551.

Campbell, C. A., McConkey, B. G., Zentner, R. P., Selles, F. and Dyck, F. B. 1992. Benefits of wheat stubble strips for conserving snow in southwestern Saskatchewan. J. Soil Water Conserv. **47**: 112-115.

Campbell, C. A., Selles, F., Zentner, R. P. and McConkey, B. G. 1993a. Available water and nitrogen effects on yield components and grain nitrogen of zero-till spring wheat. Agron. J. **85**: 114-120.

Campbell, C. A., Zentner, R. P., Selles, F., McConkey, B. G. and Dyck, F. B. 1993b. Nitrogen management for spring wheat grown annually on zero-tillage: yields and N use efficiency. Agron. J. **85**: 107-114.

Cutforth, H.W., Jefferson, P.G. and Campbell, C.A. 1991. Lower limit of available water for three plant species grown on a medium-textured soil in southwestern Saskatchewan. Can. J. Soil Sci. **71**: 247–252.

Dyck, F. B. and Tessier, S. 1986. Zero-till development at the Swift Current Research Station. Can. Soc. Agric. Eng., Ottawa, ON, Paper 86-210.

Follett, R. F. 1989. Nitrogen management and groundwater protection. Elsevier, New York, NY, Developments in Agricultural and Managed-forest Ecology 21.

Follett, R. F., Keeney, D. R. and Cruse, R. M. 1991. Managing nitrogen for groundwater quality and farm profitability. Soil Sci. Soc. Am., Madison, WI.

Germon, J. C. 1989. Management systems to reduce impact of nitrates. Elsevier Applied Science, London, U.K.

Hamm, J. W., Radford, F. G. and Halstead, E. H. 1970. The simultaneous determination of nitrogen, phosphorus and potassium in sodium bicarbonate extracts of soils. Pages 65–69 *in* Technicon International Congress: Advances in Automatic Analysis. Futura Publ. Co., Mount Kisco, NY, Industrial Analysis 2.

Hedlin, R. A., and Cho C. M. 1974. Fertilizer use and other soil management practices in relation to contamination of ground and surface water with nitrogen and phosphorus. Pages 303–323 *in* Allocative conflicts in water resource management. Agassiz Centre for Water Studies, University of Manitoba, Winnipeg, MN.

Linville, K. W. and Smith, G. E. 1971. Nitrate content of soil cores from corn plots after repeated nitrogen fertilization. Soil Sci. **112**: 249–255.

Little, T. M. and Hills, F. J. 1978. Agricultural experimentation -- Design and analysis. John Wiley & Sons, New York, NY.

McMahon, M. A. 1988. Fertilizer use and high yields are compatible with quality environment. Better Crops Plant Food **72**: 3–8.

Phillips, R. E., Blevins, R. L., Thomas, G. W., Frye, W.W. and Phillips, S. H. 1980. No-tillage agriculture. Science **208**: 1108–1113.

Saskatchewan Agriculture, Soils and Crops Branch. 1988. Phosphorus fertilization in crop production. Agdex 541, Regina, SK.

Schlegel, A. and Dhuyvetter, K. 1992. Phosphorus boosts long-term corn and sorghum yields, reduces soil nitrate carryover. Better Crops Plant Food **76**(1): 16–19.

Thomas, G. W., Blevins, R. L., Phillips, R. E. and McMahon, M. A. 1973. Effect of a killed sod mulch on nitrate movement and corn yields. Agron. J. **65**: 736–739.

Zentner, R. P. and C. A. Campbell. 1988. First 18 years of a long-term crop rotation study in southwestern Saskatchewan - yields, grain protein, and economic performance. Can. J. Plant Sci. **68**: 1–21.