Long-term influence of cropping systems, tillage methods, and N sources on nitrate leaching

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Izaurralde, R. C., Feng, Y., Robertson, J. A., McGill, W. B., Juma, N. G. and Olson, B. M. 1995. **Long-term influence of cropping systems, tillage methods, and N sources on nitrate leaching**. Can J. Soil Sci. **75**: 497–505. The extent of nitrate leaching in cultivated soils of Alberta is unknown. We studied how long- and short-term agricultural practices influenced nitrate leaching in a cryoboreal subhumid soil-climate of north-central Alberta. The study used plots from three crop rotation-tillage studies at Breton on an Orthic Gray Luvisol, and from one at Ellerslie on an Orthic Black Chernozem. Soil samples were taken in the fall of 1993 from selected treatments as well as native forest sites in 0.3-m depth increments from 0 to 3.9 m and analyzed for NO_3-N. No NO_3^- were found under native forest vegetation. NO_3-N accumulated below 0.9-m depth of agricultural ecosystems cultivated for as long as 64 yr ranged from 0 to 67 kg N ha^{-1}. At Breton, fallow-wheat rotation plots receiving fertilizer N and manure contained eight times more NO_3-N below 0.9 m depth than non-fertilized plots. NO_3-N levels in an 8-yr legume-based rotation and in continuous-barley plots were similar but greater than in continuous-forage plots. Eighty-seven percent of NO_3^- found under continuous barley occurred below the root zone compared with only 35% in the 8-yr rotation. At Ellerslie, NO_3-N mass was related to fertilizer N and mineralization of soil organic matter. Increased efforts should be directed towards better synchronizing N release from or addition to soils with plant uptake. Evidence of greater nitrate leaching under zero tillage than under conventional warrants further confirmation.

Key words: Nitrogen loss, fallow, *Hordeum vulgare* L., *Triticum aestivum* L., manure, legumes, synthetic fertilizer

Izaurralde, R. C., Feng, Y., Robertson, J. A., McGill, W. B., Juma, N. G. et Olson, B. M. 1995. Can. J. Soil Sci. **75**: 497–505. On ne connaît pas l'ampleur du lessivage des nitrates dans les sols cultivés de l'Alberta. Nous avons donc examiné dans quelle mesure les pratiques agricoles de longue et de courte durée influent sur le lessivage des nitrates dans un environnement pédoclimatique subhumide cyroboréal du centre-nord de l'Alberta. Nous utilisions des parcelles appartenant à trois études rotation-travail du sol, conduites à Breton dans un Luvisol gris orthique et à une étude conduite à Ellerslie dans un Chernozem noir orthique. Des échantillons de sol prélevés à l'automne 1993 dans certains traitements de culture, de même que sous forêt naturelle, par tranches de 0,3 m, allant de 0 à 3,9 m de profondeur étaient analysés sur leur teneur en N nitrique. Aucune trace de nitrate n'était observée sous couvert forestier. Le N nitrique accumulé en dessous de 0,9 m dans les agroécosystèmes en culture depuis aussi loin que 64 années fluctuait entre 0 et 67 kg N ha^{-1}. À Breton, le sol des parcelles en rotation jachère-blé recevant du N sous forme d'engrais chimique et de fumier contenait 8 fois plus de N-NO_3 en dessous de la barre de 0,9 m que les parcelles non fertilisées. Les concentrations de N nitrique dans une rotation de 8 ans incluant une légumineuse et dans un assolement d'orge en continu étaient semblables, mais elles étaient supérieures à celles mesurées dans les assolements sous culture fourragère en continu. Quatre-vingts-sept p. 100 des nitrates retrouvés sous orge en continu se situaient en dessous de la rizhosphère, contre seulement 35% dans la rotation de 8 ans. À Ellerslie, la masse du N nitrique était reliée au N de fumure et à la minéralisation de la matière organique du sol. Une plus grande attention devrait être portée à la synchronisation du relargage du N du sol ou de la fumure N avec les demandes des cultures. Bien qu'on ait constaté un lessivage plus important des nitrates en régime de culture sans labour qu'en régime de travail du sol classique, ces tendances ont besoin d'être examinées plus à fond.

Mots clés: Déperdition de N, jachère, *Hordeum vulgare* L., *Triticum aestivum* L., fumier, légumineuse, engrais de synthèse

Nutrient supply or return to agricultural systems is essential for maintaining long-term productivity. Of all the required plant nutrients, nitrogen is perhaps the most important, because it controls rates of plant growth and development. Nitrogen, in its various oxidation states, cycles through organisms, soils, water, and air. Thus, it can be both an essential element for life as well as a contaminant. The two greatest environmental concerns about nitrogen are (i) contribution of N_2O to the greenhouse effect (Rhode 1990) and the destruction of the ozone layer (Crutzen and Ehhalt 1977); and (ii) contamination of groundwater due to nitrate leaching (Addiscott et al. 1991).

Leaching and groundwater contamination by NO_3^- has been documented worldwide. Although most examples of nitrate leaching come from humid regions (e.g. Bernhard et al. 1992; Jemison and Fox 1994; Milburn and Richards 1994; Wendland et al. 1994), irrigation and short rotations which include a fallow phase have also been associated with groundwater contamination by NO_3^- (Bauder et al. 1993; Spalding and Exner 1993). Nitrates have leached below the root zone in the semi-arid region of Saskatchewan. For example, Campbell et al. (1984) calculated, based on mineral-N analysis of soil samples taken from a fallow field at different times over the 1982 growing season, that 123 kg ha^{-1} of NO_3-N had moved below the top 2.4 m of soil. Akinremi et al. (1993) simulated nitrate leaching and water percolation under a fallow-wheat rotation at Swift Current from 1967 to 1991. The simulations predicted that a total of 121 kg ha^{-1} of NO_3-N moved below the root zone over the 25-yr period. Long-term practice of summerfallow also induced

Table 1. Description of crop rotation studies used and treatments sampled

Rotation length (yr)	Rotation[z] sequence	N source[y]	N added per rotation cycle[x] (kg ha-1)	Tillage system	Rotation phase[w] or no. replicates sampled
		Classical Plots at Breton (initiated in 1938/39)			
2	WF	Nil	0	Conventional	W, F
2	WF	Manure	173	Conventional	W, F
2	WF	Fertilizer	91	Conventional	W, F
5	WOBHH	Nil	0	Conventional	W, O
5	WOBHH	Manure	169	Conventional	W, O
5	WOBHH	Fertilizer	177	Conventional	W, O
		Hendrigan Plots at Breton (initiated in 1981)			
8	BFaBFaBHHH	Manure	394	Conventional	B1, B2
1	B	Fertilizer	90	Conventional	2
	Clover/fescue	Fertilizer	18		2
		NSERC Plots at Breton (initiated in 1989)			
4	BIBFa	Nil	0	Deep tillage	2
1	B	Nil	0	Deep tillage	2
1	B	Fertilizer	50	Deep tillage	2
	Fescue	Fertilizer	50		2
		NSERC Plots at Ellerslie (initiated in 1989)			
4	BIBFa	Nil	0	Conventional	2
4	BIBFa	Nil	0	Zero tillage	2
1	B	Nil	0	Conventional	2
1	B	Fertilizer	50	Conventional	2
1	B	Nil	0	Zero tillage	2
1	B	Fertilizer	50	Zero tillage	2
	Fescue	Fertilizer	50		2

[z]WF = wheat – fallow; WOBHH = wheat – oat – barley underseeded to alfalfa/brome mixture – established alfalfa/brome cut for hay (2 yr, H symbol); BFaBFaBHHH = barley – fababean – barley – fababean – barley underseeded to clover/brome mixture - clover/brome mixture cut for hay (3 yr); B = continuous barley; BIBFa = barley – barley intercropped with field pea – barley – fababean.
[y]N sources other than from mineralization from soil organic matter, wet/dry deposition, and biological fixation.
[x]N additions to Classical Plots has not been constant over the years. N rates applied per rotation cycle varied on average as follows: WOBHH fertilizer received N at 43 kg ha^{-1} from 1939 to 1979 and 175 kg ha^{-1} from 1980 onwards; WOBHH manure received N at 299 kg ha^{-1} from 1939 to 1979 and 175 kg ha^{-1} from 1980 onwards; WF fertilizer received N at 8 kg ha^{-1} from 1939 to 1979 and 91 kg ha^{-1} from 1980 onwards, WF manure received N at 305 kg ha^{-1} from 1939 to 1979 and 91 kg ha^{-1} from 1980 onwards. Continuous forage receive N on an annual basis.
[w]W = wheat; F = fallow; O = oat; B1 = 1st barley in rotation; and B2 = 2nd barley in rotation.

nitrate leaching in a more humid environment at Indian Head, Saskatchewan (Campbell et al. 1994). The above results strongly suggest that nitrate leaching could be a real and extensive phenomenon under Canadian Prairie conditions, even with relatively low N inputs.

Other soil management practices may influence nitrate leaching as well. While tall-stubble management (Campbell et al. 1993) and poor crop growth (Campbell et al. 1993; Campbell and Zentner 1993) appear to intensify nitrate leaching through enhanced soil moisture, legume-cereal rotations seem to lessen it due to a greater synchrony achieved between supply and demand of N (Campbell et al. 1992). In Ohio, changing from fertilizer to legumes to supply the N needed for orchardgrass or tall fescue pastures decreased the NO_3-N concentration of ground water rapidly during the first 2 yr, followed by a more gradual decline for the next 8 yr (Owens et al. 1994). Adams et al. (1994) studied judicious use of manure in combination with fertilizers at a site in Arkansas, and reported that such a system may eliminate nitrate leaching. In contrast, however, in Maryland over-application of manure either to supply N for expected higher demands of irrigated corn or to dispose of the manure (Weil et al. 1990) and in central Pennsylvania use of manure in combination with fertilizers at economic optimum rates of N (Jemison and Fox 1994) were associated with nitrate leaching and ground water contamination. Interactions among management and the physical environment are often complex and therefore site specific. The objective of this study was to evaluate how long- and short-term management practices influence nitrate leaching in the cryoboreal subhumid soil-climate of north-central Alberta.

MATERIALS AND METHODS

Description of Long-term Cropping System Studies

We selected treatments from long-term plots at the University of Alberta Breton Plots (53°07'N, 114°28'W) and at the Ellerslie Research Station (53°25'N, 113°33'W). The soil at Breton is an Orthic Gray Luvisol mapped as the Breton loam series on a 3% slope; the soil at Ellerslie is an Orthic Black Chernozem mapped as the Malmo clay loam series on a 1% slope. Breton has a long-term annual precipitation of 547 mm and a potential evapotranspiration close to the annual precipitation. At Ellerslie the long-term annual precipitation is 452 mm and the potential evapotranspiration is 486 mm. The three long-term plots examined at Breton were the Classical Plots, the Hendrigan Plots, and the Natural-Sciences and Engineering Research Council

Table 2. Soil bulk density at the two study sites as determined in this and two other studies, and as available from the Alberta Soil Layer Digital data

Mid-point depth (m)	This study	Standard error	Previous studies	Soil layer digital data
	Mg m^{-3}			
		Breton		
0.15	1.4	0.04	1.5[z]	1.4[y]
0.45	1.5	0.03	1.6	1.5
0.75	1.6	0.02	1.6	1.5
1.05	1.6	0.04	1.6	
1.35	1.5	0.03	1.6	
1.65	1.6	0.03		
1.95	1.6	0.11		
2.25	1.8	0.04		
2.55	1.9	0.03		
2.85	1.9	0.03		
3.15	1.9			
3.45	1.9			
3.75	2.0			
		Ellerslie		
0.15	0.9	0.01	1.2[x]	1.1
0.45	1.3	0.04	1.4	1.3
0.75	1.4	0.06	1.6	1.5
1.05	1.3	0.07	1.6	1.5
1.35	1.3	0.06		1.5
1.65	1.3	0.04		
1.95	1.2	0.06		
2.25	1.3	0.05		
2.55	1.4	0.07		
2.85	1.3	0.09		
3.15	1.4	0.07		
3.45	1.3	0.01		
3.75	1.7	0.17		

[z] Miller (1984).
[y] Alberta Soil Layer Digital File (1989).
[x] Maulé (1984). Values presented here were interpolated using depth as weight.

(NSERC) Plots. The long-term plots used at Ellerslie were the NSERC Plots, similar in design to those at Breton. Details of treatments and plots sampled are given in Table 1.

The Classical Plots were initiated in 1930 to find "systems of farming suitable for the wooded soil belt" (Wyatt et al. 1936). The experimental setup allows for long-term productivity comparisons between a 5-yr rotation of spring wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.) underseeded to alfalfa (*Medicago sativa* L.) / brome (*Bromus inermis* Leyss.) mixture followed by two more years of the hay mixture; and a 2-yr rotation of spring wheat and summerfallow (McGill et al. 1986; Wani et al. 1994; Juma et al. 1995). These two rotations are identified as WOBHH and WF, respectively. Each rotation is subdivided into three subtreatments on the basis of nutrient additions: (i) nil (C), (ii) commercial fertilizers containing N, P, K, and S (F), and (iii) cattle manure calculated to add the same amount of N as applied with commercial fertilizers (M). Details of N application rates are given in Table 1 and a soil map, plot layout, and crop x year grid are provided in Wani et al. (1994). Fertilizer N is added to the cereal crops within each rotation. Prior to 1980, cattle manure was added in the fall once every 5 yr to both phases in the WF rotation and after plowing down of the alfalfa/brome mixture in the WOBHH rotation. After 1980, the manure application in the latter rotation was split equally into two at the end of the oat crop and the alfalfa/brome mixture. As per original design, all aboveground biomass is harvested and removed from the plots; i.e., grain, straw and forage cuts.

The Hendrigan Plots at Breton were established in 1980 to compare crop productivity and changes in soil properties among: (i) an 8-yr rotation (BFaBFaBHHH) of barley, fababean (*Vicia faba* L.), barley, fababean, barley underseeded to a red clover (*Trifolium pratense* L.) / brome (*Bromus inermis* Leyss.) mixture followed by 3 more years of this forage crop (Wani et al. 1994); (ii) a continuous monoculture barley (B) fertilized annually with N; and (iii) a continuous grass-legume system of creeping red fescue (*Festuca rubra* L.) and white Dutch clover (*Trifolium repens* L.) (Wani et al. 1991). N application rates and sources are given in Table 1. Amounts of cattle manure applied to plots of the 8-yr rotation are calculated as 70% of the N removed as straw from year 5 and forages from years 6 through 8 and applied in the fall of the eighth year (Wani et al. 1994). Equivalent amounts of N applied in manure have ranged from 190 to 524 kg ha^{-1} over a 10-yr period (1981–1989).

The NSERC Plots were established at Breton and Ellerslie in 1986 to determine the agronomic performance and soil-plant interactions of: (i) barley, (ii) barley intercropped with field pea (*Pisum sativum* L.), (iii) faba bean, and (iv) red fescue (Dinwoodie and Juma 1988; Izaurralde et al. 1993). The study was modified in 1989 to examine the

Table 3. Mass of nitrate-N found in the 0.9–3.9 and 0–3.9 m depth intervals under various crop rotations, tillage, and N amendments

Treatment	Depth intervals (m) Subtreatment	0.9–3.9	0–3.9
		kg ha^{-1} of NO_3-N	
		Classical Plots at Breton	
WF	Nil	5*b,x*[z]	8*b,y*$^{(P<0.094)}$
WF	Manure	36*a,x*	59*a,x*
WF	Fertilizer	42*a,x*	46*a,x*
WOBHH	Nil	4*a,x*	21*b,x*
WOBHH	Manure	14*a,x*	41*ab,x*
WOBHH	Fertilizer	22*a,x*	66*a,x*
		Hendrigan Plots at Breton	
BFaBFaBHHH	Manure	10*b*[y]	29*a*
B	Fertilizer	35*a*	40*a*
Clover/brome	Fertilizer	0*b*	0*b*
		NSERC Plots at Breton	
BIBFa	Nil	0*a*	9*a*
B	Nil	17*a*	31*a*
B	Fertilizer	18*a*	27*a*
Fescue	Fertilizer	13*a*	13*a*
		NSERC Plots at Ellerslie	
BIBFa, CT	Nil	38*ab*	58*abc*
BIBFa, ZT	Fertilizer	46*ab*	63*ab*
B, CT	Nil	24*ab*	38*abc*
B, CT	Fertilizer	32*ab*	58*abc*
B, ZT	Nil	36*ab*	57*abc*
B, ZT	Fertilizer	67*a*	88*a*
Fescue	Fertilizer	13*b*	13*c*

[z]For Classical Plots comparisons. Unless exact probability is specified, means within same depths followed by the same letter are not significantly different following a *t*-test at $p<0.05$;letters *a-b* are used to compare treatments within a rotation; letters *x-y* are used to compare fertility treatments between rotations.
[y]For Hendrigan and NSERC Plots comparisons. Means, within same study and depths, followed by the same letter are not significantly different following a protected Fisher's LSD test at $P<0.05$.

Table 4. N additions and removals on Classical Plots at Breton over 50 yr (1940–1989)[z]

Treatment	WF Added	WF Removed	WF 'Net' removal	WOBHH Added	WOBHH Removed	WOBHH 'Net' removal
	kg ha^{-1}					
Nil	0	773	773	0	1517	1517
Manure	1622	1603	-19	2801	3322	521
Fertilizer	625	1399	774	733	3357	2624

[z]Source: Robertson et al. (unpublished data).

performance of these crops when grown in rotation (Izaurralde et al. 1995). The 4-yr rotation established consisted of barley, barley intercropped with field pea, barley, and fababean (BIBFa). This rotation was practiced under two tillage regimes at each site. At Breton the tillage treatments were **conventional** (**CT**, using implements such as chisels, cultivators, and harrows for seedbed preparation) and **deep tillage** (**DT,** same as CT but chisel pass was 0.25 m deep to promote clay enrichment of Ap horizon). The DT treatment was selected for this study. At Ellerslie, the tillage regimes were conventional tillage (as described above) and **zero tillage** (**ZT**, only soil disturbance caused by double-disc drill when sowing). Crops in these rotations were not fertilized with N. Continuous **barley plots** (**B**) were also established in 1989 under these two tillage regimes, with and without N additions, to allow for direct comparisons with the barley crops grown in the 4-yr rotations.

In order to compare nitrate distribution with depth in the cropping systems to natural ecosystems, we also sampled several nearby sites under native vegetation at both Breton and Ellerslie. Native vegetation around the Ellerslie area corresponds to the Aspen Grove Section (Crown and Greenlee 1978) where trembling aspen (*Populus tremuloides*) is abundant in natural stands. Native vegetation in the Breton area corresponds to the Lower Foothills Section with a variable mixture of trembling aspen, balsam poplar (*Populus balsamifera*), white birch (*Betula papyrifera*) and white spruce (*Picea glauca*).

Soil Sampling and Analyses

Soil samples were collected during September-October 1993, after harvest and before any cultivation, from selected crop phases and fertility treatments of the above four crop rotation/tillage studies and from native sites (Table 1). Growing-season precipitation in 1993 recorded at both sites was 80% of the long-term normal. Composite samples were taken from each plot by combining three randomly extracted soil cores. Soil was sampled in 0.3-m depth increments from 0 to 3.9 m

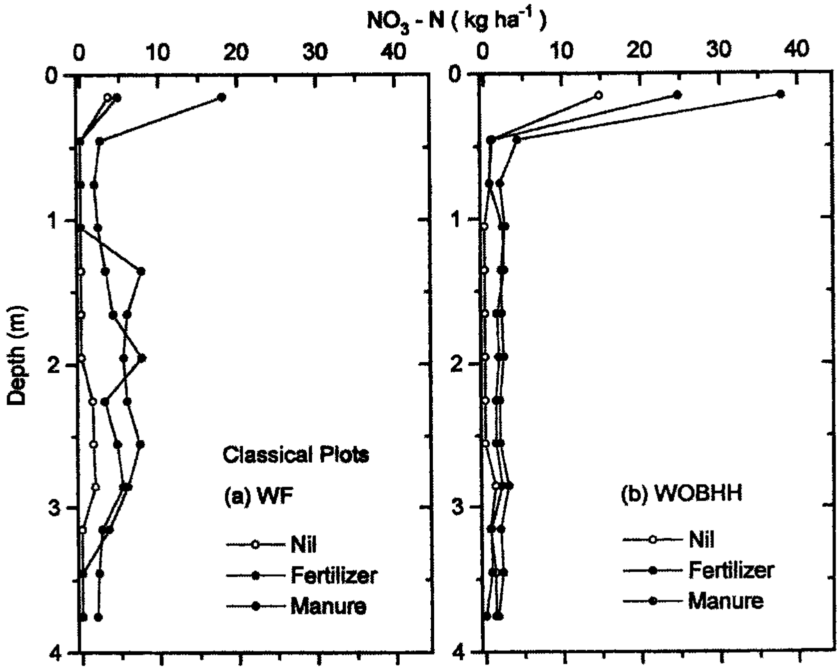

Fig. 1. NO_3-N distribution with soil depth in Classical Plots at Breton (Alberta): (a) FW, 2-yr crop rotation of wheat–fallow, and (b) WOBHH, 5-yr crop rotation of wheat–oat–barley–alfalfa/brome–alfalfa/brome.

using a heavy-duty soil corer mounted on a truck. Internal diameter of the coring tube was 67 mm. For each depth increment, an intact-as-possible subsample was taken for bulk density determination. The composite soil samples for nitrate analysis were air-dried for 96 h and then passed through a 2-mm sieve. The soil samples were analyzed for NO_3-N using an autoanalyzer with Technicon Method 497-77A (Technicon Industrial Systems 1977). Bulk-density values from earlier studies by Miller (1984) at Breton, and by Maulé (1984) at Ellerslie were compared with those obtained in this study.

Experimental Designs and Statistical Analyses

The Classical Plots were originally laid out as a series of non-replicated treatments with all rotation phases present every year. Plots were split in half in the fall of 1974 and one of them was limed to bring soil pH up to 6.5. Both halves were sampled. Statistical comparisons of NO_3^- mass data from the Classical Plots were obtained using a paired *t*-test with rotation phases and liming sub-treatments as replicates (four in total).

The Hendrigan Plots consist of eight plots containing all phases of the 8-yr rotation within a year and three plots each of continuous barley and Dutch clover/fescue. Nitrate-mass data were analyzed as one-way ANOVA with three reatments and two replications arranged in a completely randomized design.

NSERC-Plots treatments are laid out in two blocks with all crop-rotation phases present every year. NO_3-N data were analyzed as one-way ANOVA with three treatments and two replications arranged in a randomized complete block design. Unless otherwise stated either in the text or in the tables, the level of statistical significance adopted for all comparisons was 5%.

RESULTS AND DISCUSSION

Conversions of Nitrate Concentration to Nitrate Mass

Calculation of soil bulk density is a required step to convert nitrate concentration to nitrate mass. Observed bulk densities were compared with those from previous studies by Maulé (1984), Miller (1984) and the Alberta Soil Layer Digital File (1989). Values obtained at Breton within the first meter depth were in relatively good agreement with those previously published (Table 2). Bulk density values below 1-m depth increased from 1.6 to 2.0 Mg m^{-3}. Bulk densities obtained at Ellerslie within the first meter were somewhat smaller than the other data sets previously published. More noticeably, bulk density values between 1.2-m and 3.6-m depth fluctuated around 1.3 Mg m^{-3}, values unexpectedly low. Given these constraints, published values by Miller (1984) and Maulé (1984) were adopted for mass calculations. Bulk-density values below 1 m were assumed to remain constant. At each site, the bulk-density value within the 0.8–1.0 m depth range was assigned to all soil layers lying between 1.0 and 3.9 m.

Tillage reduces soil density in the cultivated layer. At Ellerslie, Haderlein et al. (1993) detected a difference of 0.1 Mg m^{-3} in the first 0.076 m depth between no-tillage (1.0 Mg m^{-3}) and tillage (0.9 Mg m^{-3}) treatments of the NSERC rotation reported in this study. Bulk density results of another no-tillage study at this site (Nyborg et al. 1995a) suggested bulk density differences do not extend beyond 0.15 m. The influence of tillage on bulk density of a 0.3-m-thick slice at the end of the growing season was assumed to be small and therefore not incorporated in the calculations.

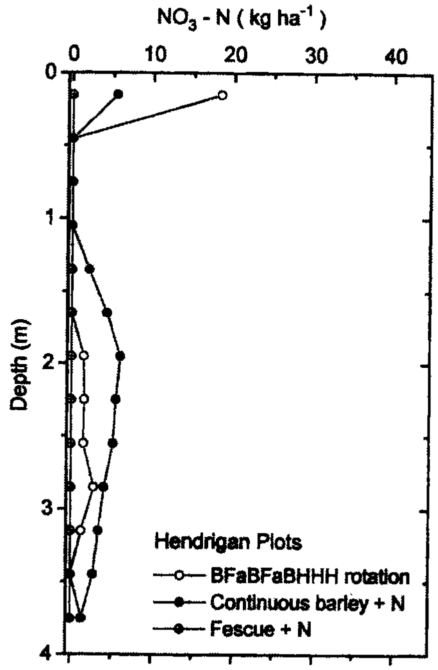

Fig. 2. NO_3-N distribution with soil depth in Hendrigan Plots at Breton, Alberta. BFaBFaBHHH, an 8-yr crop rotation of barley–fababean–barley–fababean–barley–clover/brome–clover/brome–clover/brome.

Mass of Nitrate-N in Soil Under Various Crop Rotations

Similar to findings reported by Campbell et al. (1975) in a native-grass ecosystem near Swift Current, Saskatchewan, soil samples taken under native vegetation at Breton and Ellerslie contained no NO_3^-. Although these results were somewhat expected, the reasons are not clear. Haynes (1986), in reviewing the cycling of NO_3^- in plant-soil systems, concluded nitrification had a minor role in the N cycle of many natural ecosystems. Allelochemicals, nutrient deficiencies (e.g., phosphorus), and a limiting supply of NH_4^+ have been proposed as nitrification controllers of natural ecosystems.

In contrast with the native sites, most of the cultivated systems accumulated NO_3^- in various quantities and at various depths (Table 3). Mass of NO_3-N in the entire soil profile (0-3.9 m) of the Classical Plots treatments varied eightfold between 8 kg ha^{-1} in WF nil and 66 kg ha^{-1} in WOBHH fertilizer. Mass of NO_3-N below the 0.9-m depth (the approximate rooting depth of cereals) varied significantly from 5 to 42 kg ha^{-1} in the nil and fertilizer treatments of the WF rotation, respectively.

Because of a more favorable water regime at Breton, NO_3-N quantities were smaller than those reported under the same soil management by Campbell et al. (1975, 1984) at Swift Current, Saskatchewan, and Johnston and Janzen (1993) at Lethbridge, Alberta. Two reasons are offered to explain this apparent paradox. The first is that Gray Luvisol soils are notoriously low in N-supplying power (McGill et al. 1986; Nyborg et al. 1995b). The second evolves from an overall negative balance between N additions and removals as calculated by Robertson et al. (unpublished data) in Table 4 over a 50-yr period (1940–1989).

On average, the WF fertilizer and manure rotations had eight times more NO_3-N below 0.9 m depth than the WF nil rotation (39 vs. 5 kg ha^{-1} of NO_3-N, $P < 0.06$). WOBHH fertilizer plots also contained more NO_3-N in the 0–3.9 m depth range than WOBHH nil plots ($P < 0.04$). However, the statistical comparison of NO_3-N in the 0.9–3.9 m depth range between these two treatments was not significant at $P < 0.05$. Manure did not influence NO_3-N content in the WOBHH rotation irrespective of the depth range considered, although values for the manure treatment tended to exceed those of the control and were generally less than those of the fertlized system. Although rotation had no significant effect on soil NO_3-N, nutrient-amended plots of the WF rotation tended to have more NO_3-N ($P < 0.3$) below 0.9 m than similar plots of the WOBHH rotation. It appears then that a continuous plant cover and a more extensive soil exploration by roots of perennial forages prevented NO_3^- from accumulating below 0.9 m. This is even more striking if we consider that N inputs in the WOBHH rotation were enhanced by biological-N fixation during the alfalfa/brome phase. This forage mixture increased the active N fraction in the soil (Wani et al. 1994) but apparently did not promote NO_3^- movement below 0.9 m. A pertinent observation is that the soil NO_3-N found in the rotation with forages was small compared with the N that cycled during 60 yr through the plant-soil system (Tables 3 and 4).

The Hendrigan Plots have a much shorter history than the Classical Plots. On average, the Hendrigan Plots contained less NO_3^- than the Classical Plots (Table 3), a finding likely associated with cropping history. In a similar comparison, but in the Brown soil zone, Campbell et al. (1975) detected nitrate bulges with depth about 14–18 yr after the land was broken and cropped. They also found that NO_3^- continued to accumulate even after 35 yr of cropping to a wheat summerfallow rotation. In our study, NO_3-N amounts in the 8-yr rotation and the continuous barley system were similar but significantly higher than in the continuous forage system. Eighty-seven percent of the NO_3-N found in the barley system occurred below 0.9 m compared with 35% in the 8-yr rotation. Annual N additions of 90 kg ha^{-1} to continuous barley totalled 1170 kg ha^{-1} over a 13-yr period. In contrast, the 8-yr rotation was specifically designed to satisfy most N requirements of plants via atmospheric-N fixation (2 yr of fababean and 3 yr of a clover/brome mixture). Under conditions of low soil-N availability and favorable moisture conditions, such as those at Breton, fababean can fix up to 150 kg ha^{-1} yr^{-1} of atmospheric N (Gu 1988; Izaurralde et al. 1995). After a 20-wk soil incubation study, Wani et al. (1994) found greater mineral-N accumulation in the 8-yr rotation than in the continuous barley system. In spite of this rotation having the potential to release more mineral N into the soil solution than the continuous cereal system, we suspect this release is better synchronized with plant uptake (Campbell et al. 1992). Barley yields obtained in the 8-yr rotation were consistently greater than in the continuous cereal system (Wani et al 1994). Therefore, the continuous

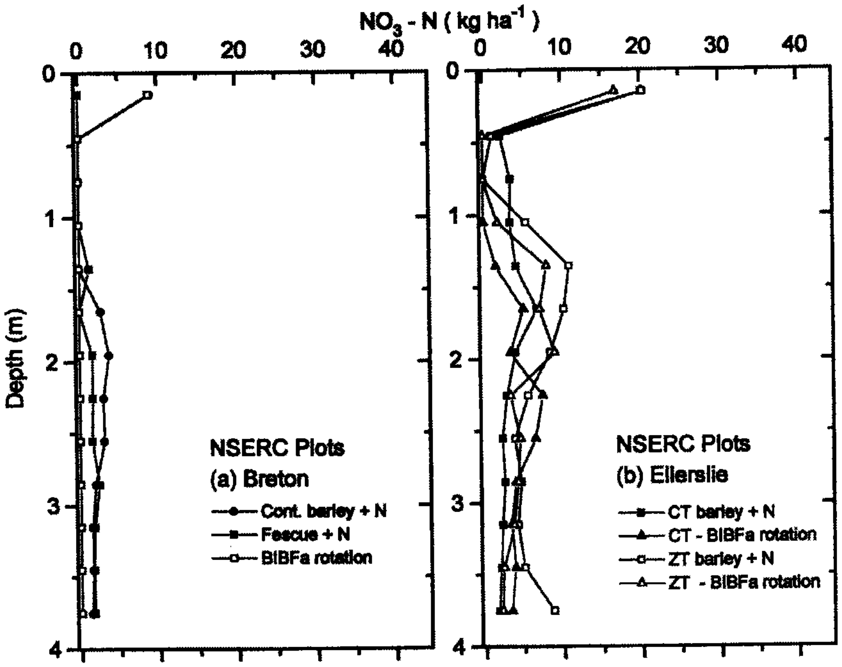

Fig. 3. NO_3-N distribution with depth in NSERC Plots at (a) Breton and (b) Ellerslie, Alberta. CT, conventional tillage; ZT, zero tillage; BIBFa, a 4-yr crop rotation of barley–barley/field pea intercrop–barley–-fababean.

barley system was less productive in terms of barley growth and appeared to be more leaky with respect to NO_3^-. Similarly, Craig and Weil (1993) reported from a field study in Maryland that a system relying on nitrogen fixation from a winter legume and relay-cropped soybeans seeded into standing wheat was associated with lower nitrate concentrations in ground water than was a 2-yr rotation of corn/winter wheat/double crop soybean.

The NSERC Plots were sampled in the fifth year of the study. Two major distinctions between this rotation and the Classical and Hendrigan Plots are: (i) the absence of perennial forage crops and (ii) presence of, at one of the sites, zero tillage treatments. At Breton, NO_3-N amounts were small with no evident distinction among treatments (Table 3). Approximately one-half of NO_3-N under continuous barley was below 0.9 m. It appears, however, that NO_3^- found below 0.9 m were derived both from fertilizer and from mineralization of soil organic matter because the NO3-N amounts in the 0.9–3.9 m depth were not sinificantly different for fertilized and non-fertilized barley, both at Breton and Ellerslie. Further, Nyborg et al. (1995b) estimated, from plant-N uptake values, the annual rate of net-N mineralization of the Orthic Black Chernozem at Ellerslie to be approximately double that of the Orthic Gray Luvisol at Breton (45 and 21 kg ha^{-1}, respectively).

At Ellerslie, there was increased nitrate leaching under zero-tilled soil (Table 3). Haderlein et al. (1993) studied water transmission at low pressure potentials through undisturbed soil cores and found that soil under ZT transmitted water faster than soil under CT. It is hypothesized that a more continuous pore system under ZT could have facilitated the movement of NO_3^- via macropore flow (Addiscott 1991). This hypothesis requires further testing to confirm its validity.

Distribution of NO_3-N with Depth under Various Crop Rotations

While analysis of NO_3-N mass values allows for quantitative comparisons of nitrate leaching among treatments, the study of the distribution of NO_3-N with depth gives insight about nitrate leaching dynamics. High concentrations of NO_3^- in aquifers have been associated with previous land use (Cameron and Wild 1982; Haynes 1986). Soil under the WF rotation exhibited more distinct NO_3^- peaks at around 2 m depth than did soil under the WOBHH rotation (Figs. 1a and 1b). We suggest that NO_3^- movement in the WF rotation occurs mostly during fallow periods having sufficient precipitation to lead to drainage events. In the WOBHH rotation, however, a more surficial NO_3^- distribution and a lack of a distinct NO_3^- peak with depth suggest less opportunity for nitrate leaching. N source (fertilizer N and cattle manure) did not appear to influence distribution of NO_3^- with depth.

Discrete NO_3^- peaks also appeared in the more recent Hendrigan Plots (Fig. 2), especially in the continuous barley system at a depth of 2 m. The presence of small NO_3^- peaks around the same depth under the NSERC Plots at Breton (Fig. 3a) suggest that nitrate leaching events are associated not only to specific management but also to rapid drainage events that may take place during periods of intense precipitation and incomplete crop cover. This is consistent with observations reported by Weil et al. (1990), Spalding and Exner (1993), and Milburn and Richards (1994).

At the NSERC Plots at Ellerslie, the NO_3^- peaks in CT and ZT fertilized-continuous barley and BIBFa rotation occurred around a depth of 1.4 m (Fig. 3b). This might be related to the considerably lower annual precipitation at Ellerslie than at Breton. Maulé et al. (1994) established, using the stable isotopes ^{18}O and deuterium, that ground water at Ellerslie contained appreciable amounts of snow water in its composition, supporting the concept that winter precipitation contributes to groundwater recharge. The implication is that significant nitrate leaching may occur between growing seasons. In more temperate-humid climates, grass cover crops lower residual mineral N between late fall and early spring thereby reducing potential for NO_3^- leaching (Shipley et al. 1992). Under cold sub-humid climates, however, the strategy perhaps to minimize nitrate leaching would be to improve synchronization among soil-N mineralization, N additions from given sources (fertilizer, manure, or symbiotic fixation), and plant-N uptake.

CONCLUSIONS

Several conclusions can be formulated on the basis of the data presented and discussed. First, there was no indication of nitrate leaching under native vegetation of aspen, poplar, white birch, and spruce at Breton and Ellerslie. Second, NO_3^- accumulated below 0.9 m of cultivated agricultural ecosystems, but quantities were small compared with N quantities that cycled through plant-soil systems over decades. Third, agronomic practices such as fallow favored nitrate leaching, while use of perennial forages tended to reduce it. Fourth, NO_3^- accumulations with depth appeared to originate not only from commercial fertilizers but also from other N sources such as manure and soil organic matter. The implication of the last conclusion is that increased efforts should be made to better synchronize N release from, or addition to, soils with plant uptake. This could be achieved by improving our capability of predicting N mineralization from soil organic matter and crop residues and by timing N release from N fertilizers with special coatings. Evidence of greater nitrate leaching under ZT than under CT warrants confirmation.

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