Nitrogen balance and accumulation pattern in three contrasting prairie soils receiving repeated applications of liquid swine and solid cattle manure

C. Stumborg · J. J. Schoenau · S. S. Malhi

Abstract The expansion of intensive livestock operations in western Canada has increased concerns about overloading of nutrients in manured lands. The magnitude of nutrient accumulation and its distribution in the soil profile varies with soil-climatic conditions. The objective of this study was to determine loading and distribution of manure-derived nitrogen (N) in the soil profile as influenced by repeated manure applications. Four field experiments were conducted at three sites (Dixon, Melfort and Plenty) in Saskatchewan under longer-term manure management. The four field experiments provide contrasts in soil type, climatic conditions, manure type, application and cropping history to enable the effect of these factors to be evaluated. Liquid hog manure (LHM—Experiment 1) and solid cattle manure (SCM—Experiment 2) treatments were applied annually over 8 years at Dixon (Black Chernozemic loam soil—Udic Boroll in sub-humid climate), while only LHM was applied at Plenty (Dark Brown Chernozemic heavy clay soil—Typic Boroll in semi-arid climate) over 6 years

(Experiment 3), and at Melfort (Dark Gray Luvisol silty clay loam soil—Mollic Cryoboralf in humid climate) over 5 years (Experiment 4). Soil samples were collected in the spring and autumn of 2003 and 2004, and were analyzed for organic N, ammonium-N (NH_4^+-N) and nitrate-N (NO_3^--N) concentrations. Plant samples were collected to determine the impact of manure application rate on plant N uptake and crop N removal. The annual application of LHM (37,000 L ha^{-1} yr^{-1}) and SCM (7.6 Mg ha^{-1} yr^{-1}) at agronomic rates at Dixon (added N balances crop demand for that year), or larger rates of LHM (111,000 L ha^{-1}) applied once every 3 years (Melfort) did not significantly elevate NO_3^--N in soil compared to the unfertilized control. Lower crop removal and reduced leaching of NO_3^--N due to drier conditions as occurred at the Plenty site contributed to greater accumulation of nitrate in the top 60 cm at equivalent rates compared to the other two sites. At large manure rates, excess N from the balance estimates could not be accounted for in soil organic N and was assumed to be lost from the soil-plant system. At the Dixon LHM site, deep leaching of NO_3^--N was observed at the excessive rate (148,000 L ha^{-1} yr^{-1}) up to the 150 cm depth, compared to the control. At Dixon, the large annual application rate of SCM (30.4 Mg ha^{-1} yr^{-1}) did not significantly increase NO_3^--N in the 0–60 cm soil compared to the control, which was attributed to lower mineralization

C. Stumborg · J. J. Schoenau (✉)
Department of Soil Science, University
of Saskatchewan, Saskatoon, SK, Canada S7N 5A8
e-mail: schoenau@skyway.usask.ca

S. S. Malhi
Agriculture and Agri-Food Canada, Research Station,
Melfort, SK, Canada S0E 1A0

of organic N from the SCM. Over the short and medium term, LHM application at large rates every year poses a greater risk for loading and deep migration of NO_3^--N in soil than large rates of SCM. Larger single applications made once every 3 years were not associated with accumulation or deep leaching. To prevent loading, rates of applied manure nitrogen should be reduced when crop N removal potential is diminished by high frequency of drought.

Introduction

Nitrogen (N) applied in manure is important for both agronomic and environmental reasons. As intensive livestock operations expand, the land requirement for manure disposal increases, but the dilute nutrient status and associated large transportation costs per unit of nutrient limits the feasible distance for disposal. If excessive manure application occurs on a minimal land base, it can elevate residual N levels and increase NO_3^--N losses to ground and surface water (Chang and Entz 1996). The drinking water standard for NO_3^--N is 10 mg L^{-1} and concentrations greater than this can be harmful to humans (Keeney 1982). Nitrogen in runoff water can increase eutrophication rates in fresh water resources (Weil et al. 1990). Manure rates that match crop N requirements help to minimize N loss to the environment.

Soil texture affects soil NO_3^--N movement with depth, and its potential to cause water contamination. Soils with a loamy sand texture have shown greater NO_3^--N fluxes compared to heavy clay soils (Chang and Janzen 1996; Gehl et al. 2004). However, annual precipitation amount and severity also determine the magnitude of soil NO_3^--N loss. Chang and Janzen (1996) found that under non-irrigated conditions on a clay loam soil in southern Alberta, all manure-derived N was accounted for in crop uptake, soil organic N, and soil NO_3^--N, using manure rates up to 180 Mg ha^{-1} yr^{-1}. However, under irrigation using the same rates, there was a significant amount of N lost through leaching

and volatilization. Thus, precipitation amount and frequency combined with soil texture had a significant effect on N loss.

The beneficial management practice (BMP) that producers can use to address long-term sustainability concerns is to ensure that nutrients applied in manure are equal to crop uptake requirements over a growing season. Through manure and soil sampling prior to application, producers can maintain optimum soil fertility and avoid residual N build-up and migration as NO_3^--N over time. Few studies exist that have documented rates of liquid swine manure nitrogen, crop nitrogen uptake and export, and soil conditions over a period of several years. The potential for N accumulation and leaching will depend on the soil and climatic conditions as these affect crop N removal and losses, along with manure application practices including rate, sequence and form. The objective of this study was to reveal the impact of manure rate, application frequency and form on soil N balance and accumulation pattern in the soil at three contrasting sites: Dixon, Melfort and Plenty located in Saskatchewan, Canada, where N additions and removals have been documented since the start of manure application. The experiments provide contrasts in manure type (liquid swine versus solid cattle manure at Dixon), application frequency (annual at Dixon versus once every 3 years at Melfort), and soil-climatic conditions (ranging from humid at Melfort to semi-arid at Plenty) that enable the impact of these factors to be evaluated in conjunction with rate of manure N.

Materials and methods

Site description

The three sites in this study allow comparison of the effects of manure addition along an environmental gradient, with long-term average annual precipitation as follows: Melfort > Dixon > Plenty. Lower average annual temperatures and reduced windspeeds contribute to a gradient of precipitation effectiveness that follows the same pattern.

Dixon site

The Dixon site was located at legal location NW21-37-23-W2 in east-central Saskatchewan, Canada. It was initiated in a field operating with typical oilseed–cereal cropping practices, and had no previous history of manure application. The Black Chernozemic soil (Udic Boroll) at this site was classified as a Cudworth association, formed on highly calcareous, silty, lacustrine materials of loam surface texture. In general, this site represented productive agricultural land in Saskatchewan. Long-term average annual precipitation and temperature for this area is 373 mm and 0.7°C respectively.

Melfort site

The Melfort site was located at legal location SW26-44-18-W2 in north-central Saskatchewan. The site was initiated in a field operating under typical continuous multi-crop farming practices for the region. No manure had previously been applied on this site. The soil was classified as a Kamsack/Melfort association (Dark Gray Luvisol soil—Mollic Cryoboralf), silty clay loam texture on glacial lacustrine deposits (Saskatchewan Soil Survey, 1950). Sulfur (S) deficiency was identified as a significant limitation for optimum crop growth at this site (Schoenau et al. 2004). Long-term average annual precipitation and temperature for this area is 410 mm and 0.6°C respectively.

Plenty site

The Plenty site was located at legal location SW5-33-18-W3 in west-central Saskatchewan. The soil at this site was mapped as a Regina soil association, operating under conventional cereal–pulse cropping practices typical of the area with no previous history of manure application. The soil was characterized by heavy clay texture (Dark Brown Chernozemic soil—Typic Boroll) formed on clayey lacustrine parent material. Droughty conditions that limit crop growth and yield are more common at this site than the other two. Long-term average annual precipitation and

temperature for this region is 311 mm and 2.3°C respectively.

Experimental design

Dixon site

The Dixon site was established in 1997 and contained both Liquid hog manure (LHM) and solid cattle manure (SCM) experiments. The LHM (Experiment 1) and SCM (Experiment 2) treatments were located adjacent to one another, and the experimental design for both was a randomized complete block design (RCBD) with four replications. The LHM and SCM experiments consisted of five treatments (Table 1).

The treatments at the LHM and SCM sites were applied using different techniques. The LHM was pumped into a liquid manure application tank from an unagitated, single cell, earthen manure storage unit and placed at an average depth of 8 cm using low disturbance disk openers, except for treatments with broadcast and incorporation application. The SCM was collected from a feedlot and was approximately 1 year in age and at 50% moisture content (oven-dry basis) when it was applied. The SCM was manually broadcast and incorporated into the soil with a rototilling operation.

All LHM and SCM treatments were based on crop N requirements, and the ''X'' refers to either the amount of manure that provided approximately 100 kg total N ha^{-1}, applied at a rate of 37,000 L ha^{-1} yr^{-1} (LHM) and 7.6 Mg ha^{-1} yr^{-1} (SCM), or the amount of urea fertilizer that supplied 112 kg ha^{-1} yr^{-1} of plant-available N (the fertilizer N rate typically recommended and used in the region), over one growing season. The small or $1\times$ application rate is considered an agronomic rate of manure/fertilizer that would safely meet crop N requirements without exceeding them over a growing season.

Melfort site

The Melfort site (Experiment 3) was established in 2000, thus 2004 was its fifth year of operation. Four replicated blocks of five different

Table 1 Description of Dixon liquid hog manure (LHM—Experiment 1), Dixon solid cattle manure (SCM—Experiment 2), Melfort liquid hog manure (LHM—Exper-iment 3) and Plenty liquid hog manure (LHM—Experiment 4), treatment applications in four field experiments in Saskatchewan

Experiment	Location	Duration	Treatment	Description
1	Dixon	1997–2004	1	Check—with injector pass
			2	1×[a]—LHM injected every year
			3	2×[ab]—LHM injected every year
			4	4×[b]—LHM injected every year
			5	1×—urea applied every year
2	Dixon	1997–2004	1	Check—with incorporation pass
			2	1×—SCM broadcast and incorporated every year
			3	2×—SCM broadcast and incorporated every year
			4	4×—SCM broadcast and incorporated every year
			5	1×—urea applied every year
3	Melfort	2000–2004	1	Check—with injector pass
			2	1×—LHM rate injected each year
			3	2×—LHM rate injected once every 2 years
			4	3×—LHM rate injected once every 3 years
			5	1×—urea applied every year
4	Plenty	1999–2004	1	Check—with injector pass
			2	1×—LHM injected every year
			3	2×—LHM injected every year
			4	1×—urea applied every year

[a] 1× refers to an agronomic rate of LHM or urea, equal to 37,000 L ha^{-1} and 112 kg N ha^{-1}, respectively in Experiment 1; SCM or urea, equal to 7.6 Mg ha^{-1} and 112 kg N ha^{-1}, respectively in Experiment 2; LHM or urea, equal to 37,000 L ha^{-1} and 80 kg N ha^{-1}, respectively in Experiment 3; and LHM or urea, equal to 37,000 L ha^{-1} and 40 kg N ha^{-1}, respectively in Experiment 4

[b] 2×, 3× and 4× refer to 2, 3 and 4 times the agronomic rate of LHM or SCM in a given experiment

treatments (Table 1) were set out in a RCBD. At this site, approximately 100 kg total N ha^{-1} is supplied from the manure treatment applied at a rate of 37,000 L ha^{-1}, and 80 kg N ha^{-1} was supplied from the urea treatment. Similar to the Dixon site, the 1× treatment is intended to represent an approximate balance with the crop N requirements for a growing season. At this site, the 2× and 3× rates were applied only once every second and every third year, respectively.

Plenty site

The Plenty site (Experiment 4) was established in 1999, and 2004 was the sixth year of operation. Liquid hog manure was the only manure form used, and it was sourced from a nearby earthen manure storage unit. The manure treatments were applied using a commercial liquid manure injection truck as per the Melfort and Dixon sites. Four treatments (Table 1) were applied in three blocks using a RCBD.

At this site the "X" indicates 40 kg N ha^{-1} was applied as urea treatment, while about 150 kg total N ha^{-1} was provided from the manure treatment, applied at a rate of 56,000 L ha^{-1} from 1999 to 2002, and then reduced to 37,000 L ha^{-1} from 2002 to 2004; applying about 100 kg total N ha^{-1}. The larger manure rates were used in the first 3 years of the study due to the inability of the manure application equipment to accurately apply at rates smaller than these. With modifications to the equipment, the manure rates were subsequently reduced to 37,000 L ha^{-1}. The rate of urea N applied was less than at the other two sites, owing to drier climatic conditions and reduced yield potential at this site compared to others.

Field sampling

Soil sampling was conducted in 2003 and 2004 on selected treatments. In spring of 2003 and 2004, three PVC pipe sleeves of 15 cm diameter and 15 cm depth were inserted into each plot to sample

the 0–15 cm soil depth, collected and bulked to form a single sample. In the autumn of 2003 and again in the autumn of 2004, a hydraulic punch truck was used to collect bulk samples comprised of three soil cores per plot, for three soil depths (0–15, 15–30 and 30–60 cm) in the autumn of 2003 and for five soil depths (0–30, 30–60, 60–90, 90–120 and 120–150 cm), in the autumn of 2004. All samples were stored in a refrigerator at 4°C for 1–2 days, then air dried at room temperature and passed through a 2-mm sieve prior to laboratory analysis. Bulk density was determined using the oven dry equivalent weight of soil in the cores and the volume of the cores.

Plant samples were collected at crop maturity. Sampling in each plot was conducted using a 1 m^2 quadrat placed adjacent to the location that the spring and autumn soil samples were taken. Grain and straw yields were obtained for each plot. Subsamples were ground and stored for analysis.

Manure samples were collected for the LHM applied at all three sites, and the SCM applied at Dixon. Samples were collected during manure application, chilled to 4°C and then frozen at –20°C until laboratory analysis could be conducted. All LHM application rates are expressed on a wet weight basis. The SCM application rates at Dixon are expressed on a dry weight basis, and the moisture content consisted of about 50% water by weight.

Analytical methods

Soil analysis

Total N levels in soil were determined on samples collected in spring 2003 using a standard H_2SO_4–H_2O_2 digestion method (Thomas et al. 1967). The 2M KCl extraction method (Keeney and Nelson 1982) was used to assess the total inorganic N (NO_3^--N and NH_4^+-N) amounts in the spring and autumn of 2003, and spring and autumn of 2004. Organic N was determined as the difference between total N and total inorganic N.

Manure and plant analysis

To determine N levels in LHM, SCM and plant samples, the H_2SO_4–H_2O_2 digestion was conducted (Thomas et al. 1967) every year and the NH_4^+-N in the digest from both plant and manure samples were determined using a Technicon Autoanalyzer II (Technicon Industrial Systems 1973). Multiplying the manure N concentration by the application rate each year, and the crop seed N concentration by the yield, allowed the determination of manure N inputs and crop N removal outputs, respectively, for each year of the study at each site.

Soil N balance

It is difficult to directly measure N leaching losses in long-term research trials in semi-arid environments due to the low and sometimes episodic nature of water percolation through the soil profile. Determining an N balance from the cumulative N inputs, crop N outputs, and soil NO_3^--N accumulation is more useful in understanding potential soil N fluxes over an extended period of time.

To determine the effects of annual manure application over the past 8 years at the Dixon LHM site, a simple N balance was formulated. Nitrogen inputs were calculated using the total N inputs from manure and fertilizer, and the N outputs were calculated from the seed yield multiplied by the % N concentration in the seed. The straw was returned back into the soil each year, thus it was not included in the cumulative N outputs.

The predicted residual N, attributable to manure or urea fertilizer, was determined by the difference between the total N input (manure/fertilizer) and total N removed in seed from manure or urea fertilizer. The resultant value (A) provided an indication of the accumulation or depletion of manure/fertilizer N in both the organic and inorganic fractions over the past 8 years. The residual NO_3^--N recovered in soil from manure or urea fertilizer (B) was measured in the top 0–150 cm depth for Experiments 1, 2 and 4 or 0–90 cm depth in Experiment 3, and was then subtracted from the predicted residual manure/urea N (A) to provide an estimate of the additional N that accumulated in the organic form or was lost through

volatilization, denitrification, or leaching processes over the past 8 years (A–B).

Statistical analysis

The experimental design for all experiments was a RCBD. Statistical comparisons were conducted using least significant difference (LSD) from a standard analysis of variance technique. All LSD calculations were conducted using the GLM procedure (SAS Institute Inc. 1985).

Results and discussion

Soil N balance

Dixon site

In Experiment 1, the results under (A–B) in Table 2 indicate that the agronomic rate of urea (112 kg N ha^{-1} yr^{-1}) and LHM (37,000 L ha^{-1} yr^{-1}) had less N accumulation in the organic fraction or loss in the inorganic form compared to twice (74,000 L ha^{-1} yr^{-1}) and four times (148,000 L ha^{-1} yr^{-1}) the agronomic rate of LHM. If the N in (A–B) is assumed to be lost, this amount represents about 50% of the applied N (N inputs). The control treatment showed a predicted deficit in the total soil N levels over the 8-year period.

The total soil profile NO_3^--N (0–150 cm depth) increased with increasing LHM rate (Table 2), and represented from 2 to 26% of the total applied N (N inputs). This was smaller than results by Chang and Janzen (1996) that showed accumulated NO_3^--N in the 0–150 cm depth under non-irrigated conditions to represent 29–36% of the total N applied in cattle feedlot manure. The plant availability of LHM N is around 60% (Qian and Schoenau 2000) compared to SCM which is around 30% in the year of application (Brinton 1985). Studies in Saskatchewan have shown that 30–90% of the N in LHM is present in the NH_4^+-N form, compared to only 10 to 20% in SCM (Schoenau et al. 2000). If LHM application exceeds crop N uptake, much of the excess N will be present immediately as inorganic N and

will be more susceptible to leaching and denitrification losses, compared to residual N from SCM which is immobilized in the organic fraction. From this N balance it is clear that annual application rates that exceed crop uptake are associated with soil NO_3^--N accumulation. However, agronomic rates of LHM should not result in excessive soil profile NO_3^--N.

In Experiment 2, the N balance for the Dixon SCM site (Table 2) showed distinct differences in the N distribution between the inorganic and organic fractions, compared to the LHM. The SCM total NO_3^--N levels in the 0–150 cm depth were smaller than the LHM total NO_3^--N levels. Calculations indicated that LHM NO_3^--N (0–150 cm) was at 200 and 694 kg NO_3^--N ha^{-1}, and 26 and 54 kg NO_3^--N ha^{-1} for the SCM at twice and four times the agronomic rate, respectively. However, the agronomic rate for both SCM and LHM showed similar NO_3^--N levels with soil depth. The low availability of SCM with increasing rate of application is attributed to the small inorganic N content (14%) and high volatilization losses during the broadcast and incorporation application (Mooleki et al. 2004). Other research indicates that the greater C:N ratio of SCM promotes net N immobilization and reduces the available inorganic N levels (Paul and Beauchamp 1994; Qian and Schoenau 2002). Although experiments 1 and 2 were set up side by side, they were not compared statistically because they were two separate experiments. However, general comparisons are made between them to emphasize similarities and differences in behavior of LHM and SCM sources.

The high C:N ratio also explains the large values in the (A–B) column in Table 2. These values represent the amount of N either accumulated in the organic fraction or lost from the system. When 14% of the manure applied N is inorganic and 86% is in organic form, immobilization processes are encouraged and N is stored in the soil organic matter where it mineralizes slowly and is retained at the soil surface.

Melfort site

The N balance at the Melfort LHM (no S fertilizer) site (Experiment 3) was calculated in

Table 2 Dixon liquid hog manure (LHM—Experiment 1) N balance from 1997 to 2004, Dixon solid cattle manure (SCM—Experiment 2) N balance from 1997 to 2004, Melfort liquid hog manure (LHM—Experiment 3) N balance from 2000 to 2004, and Plenty liquid hog manure (LHM—Experiment 4) N balance from 1999 to 2004

Treatment	Autumn 2004						
	Total input of N from manure or fertilizer[a]	Total output of N in seed[b]	Total N removed in seed from manure or fertilizer	Predicted residual manure/or fertilizer N[c] A	Total NO$_3$-N recovered in soil[d]	Total NO$_3$-N recovered in soil from manure or fertilizer B	(A–B)[e]
Experiment 1 (Dixon LHM)							
Control	0	137		0	19		
37,000 L ha^{-1} injected yr^{-1}	645	381	244 (37.8)[g]	401	33	14 (2.2)[g]	387
74,000 L ha^{-1} injected yr^{-1}	1,290	553	416 (32.2)	874	200	181 (14.0)	693
148,000 L ha^{-1} injected yr^{-1}	2,581	617	480 (18.6)	2,101	694	675 (26.2)	1,426
112 kg N ha^{-1} urea yr^{-1}	896	417	280 (35.0)	616	141	122 (15.3)	494
Experiment 2 (Dixon SCM)							
Control	0	157		0	29		
7.6 M g ha^{-1} broadcast-incorporated yr^{-1}	822	242	85 (10.3)	737	32	3 (0.4)	734
15.2 Mg ha^{-1} broadcast-incorporated yr^{-1}	1,644	346	189 (11.5)	1,455	26	–3 (–0.2)	1,458
30.4 Mg ha^{-1} broadcast-incorporated yr^{-1}	3,288	449	292 (8.9)	2,996	54	25 (0.8)	2,971
112 kg N ha^{-1} urea yr^{-1}	896	462	305 (38.1)	591	127	98 (12.3)	493
Experiment 3 (Melfort LHM)							
Control	0	157		0	14		
37,000 L ha^{-1} injected yr^{-1}	465	338	181 (38.9)	284	18	4 (0.9)	280
111,000 L ha^{-1} injected[f]	504	338	181 (35.9)	323	18	4 (0.8)	319
80 kg N ha^{-1} urea yr^{-1}	400	271	114 (28.5)	286	42	28 (7.0)	258
Experiment 4 (Plenty LHM)							
Control	0	118		0	156		
37,000 L ha^{-1} injected yr^{-1}	1,028	223	105 (10.2)	923	797	641 (62.4)	282
74,000 L ha^{-1} injected yr^{-1}	2,056	235	117 (5.7)	1,939	1,374	1,218 (59.2)	721
40 kg N ha^{-1} urea yr^{-1}	240	168	50 (12.5)	190	255	99 (41.3)	91

[a] Calculated from manure/fertilizer concentrations applied annually over 8 years in Experiments 1 and 2, over 5 years in Experiment 3 and over 6 years in Experiment 4; [b] Calculated from seed yield multiplied by %N concentration in seed over 8 years in Experiments 1 and 2, over 5 years in Experiment 3 and over 6 years in Experiment 4; [c] Calculated as total N input from manure or fertilizer—N removed in seed from manure or fertilizer; [d] Amount of NO$_3$-N recovered in soil in the 0–150 cm depth in Experiment 1, 2 and 4, and 0–90 cm depth in Experiment 3; [e] Difference (A–B) represents manure or fertilizer N accumulated in the organic form or lost from soil-plant system; [f] Manure was applied once every 3 years; [g] The values in parentheses are percentages of the applied N recovered

the same manner as the Dixon N balance, except the total NO$_3$-N was calculated from the 0–90 cm depth due to sampling difficulties at greater depths (Table 2). The 111,000 L ha^{-1} rate applied once every 3 years resulted in less accumulation of N in organic forms or loss from the site over the 5-year period compared to Dixon, because the large rate of LHM was applied at Melfort only

once every 3 years instead of annually (Dixon) and the history of application was shorter.

Total soil profile NO_3^--N (0–90 cm) at Melfort (column B) was the lowest compared to other sites, and revealed that 80 kg N ha^{-1} urea produced NO_3^--N levels twice as large (42 kg NO_3^--N ha^{-1}) as either the small or large rate of LHM (18 kg NO_3^--N ha^{-1}). Increased N uptake from the LHM treatments compared to the urea treatment may be attributed to the enhanced growth from other nutrients, like P and S, which were supplied in LHM and not in the urea fertilizer (Schoenau et al. 2004).

Plenty site

The N balance for the Plenty site (Experiment 4) was calculated similar to Dixon and Melfort, and the total soil profile NO_3^--N was determined for the 0–150 cm depth (Table 2). The LHM treatments showed manure N accumulation as organic N or lost over the 6-year period, in amounts less than at Dixon for the same yearly application rate. The agronomic rate (37,000 L ha^{-1} yr^{-1}) and twice the agronomic rate (74,000 L ha^{-1} yr^{-1}) of LHM had about 5 and 9 times greater total profile NO_3^--N levels, respectively, compared to the control. The heavy clay soil at Plenty combined with several dry years would have reduced losses of NO_3^--N from the soil profile. However, heavy clay soil is susceptible to deep cracking in dry conditions, and large amounts of precipitation could promote eventual deep leaching of surface accumulated NO_3^- through preferential flow.

Soil organic N

Total organic N was determined at the Dixon LHM and SCM sites in the spring of 2003, to compare to the N balance and reveal any changes in the organic N distribution with varying manure rates. In Experiment 1, there was no significant difference in soil organic N in the 0–15 cm layer with LHM treatment, however an increasing trend with manure/urea fertilizer application was noted, regardless of rate (Table 3). The increasing trend in organic N with N application (LHM or fertilizer) may be a reflection of the additional organic N supplied from increased crop uptake

and subsequent straw incorporation back into the soil over the 8-year study period. Liquid hog manure had a small organic N content, thus increasing organic N levels were likely mainly a result of increased residue return each autumn. The LHM N balance (Experiment 1—Table 2) indicated that 1,426 kg N ha^{-1} was either accumulated in the organic N fraction or lost over the 8-year period at the 148,000 L ha^{-1} yr^{-1} rate of LHM. There was no significant increase in the soil organic N in the spring of 2003 at any LHM rate, which indicated that significant losses of N by mechanisms such as volatilization, denitrification, or leaching were occurring over time.

The organic N analysis from the SCM site (Experiment 2) in the spring of 2003 (Table 3) showed no significant increase in organic N amounts above the control with the 7.6 Mg ha^{-1} yr^{-1} and 15.2 Mg ha^{-1} yr^{-1} rates of SCM, but a significant increase was noted at the largest rate, 30.4 Mg ha^{-1} yr^{-1}. The high organic matter content of SCM from the straw bedding, contributed to higher organic N in the surface soil over the 8-year period. However, the N balance from the SCM site (Experiment 2—Table 2) showed that the N increase in the organic fraction or loss from the system was equal to 2,971 kg N ha^{-1}, but in Table 3 the increase in organic N compared to the control was only 740 kg N ha^{-1}. This indicated that about 2,000 kg N ha^{-1} was unaccounted for, presumably lost through volatilization, denitrification, or leaching mechanisms.

Assessment of the soil organic N after 8 years at the Dixon LHM and SCM sites suggests that agronomic rates of manure did not result in excess N loss from the soil system. For the LHM site, nearly all of the N calculated to be lost or present in the organic matter, was accounted for in the increase in soil organic N at the agronomic LHM rate. At high manure rates, excess N from the balance estimates could not be accounted for in the organic N analysis and were assumed to be lost from the system.

Soil profile nitrate-N

Nitrate-N is water soluble and susceptible to leaching loss. When manure is annually applied at large rates that exceed crop N uptake and export,

Table 3 Amount of organic N in soil (0–15 cm) in spring 2003 with liquid hog manure (LHM—Experiment 1) and solid cattle manure (SCM—Experiment 2) treatments at Dixon, Saskatchewan

Treatment	Organic N in soil (kg N ha^{-1})	
	LHM	SCM
Control	4,487	5,038
37,000 L ha^{-1} injected[a] yr^{-1}/7.6 Mg ha^{-1} broadcast-incorporated[b] yr^{-1}	4,896	5,229
74,000 L ha^{-1} injected yr^{-1}/15.2 Mg ha^{-1} broadcast-incorporated yr^{-1}	4,755	5,571
148,000 L ha^{-1} injected yr^{-1}/30.4 Mg ha^{-1} broadcast-incorporated yr^{-1}	4,744	5,778
112 kg N ha^{-1} urea yr^{-1}	4,799	5,160
LSD$_{0.10}$	474	554

[a] LHM treatments are identified by L ha^{-1}

[b] SCM treatments are identified by Mg ha^{-1}

it can result in NO$_3^-$-N build-up near the soil surface. Large rainfall or irrigation events can redistribute NO$_3^-$-N downward in the soil profile. Soil texture, water infiltration rate and duration have a major influence on the magnitude of NO$_3^-$-N movement with depth.

Dixon site

Assessing the distribution of NO$_3^-$-N with increasing soil depth under long-term manure management can help provide an indication of potential leaching loss. As shown in Table 4, the only significant difference in NO$_3^-$-N levels in the top 0–60 cm was between the largest rate of LHM (148,000 L ha^{-1} yr^{-1}) and all other treatments, due mostly to large variability between samples (LSD$_{(0.10)}$ = 109). The agronomic rate of LHM (37,000 L ha^{-1} yr^{-1}) resulted in no significant increase in NO$_3^-$-N amounts over the control or urea at any depth increment. The largest rate of LHM (148,000 L ha^{-1} yr^{-1}) showed significantly larger NO$_3^-$-N compared to the control at all soil depths, and the urea fertilizer had significantly larger soil NO$_3^-$-N compared to the control up to the 60–90 cm depth, indicating NO$_3^-$-N leaching was occurring over time.

The 74,000 L ha^{-1} yr^{-1} and 148,000 L ha^{-1} yr^{-1} rates of LHM increased residual NO$_3^-$-N compared to the control at most soil depths (Table 4). It is important to note that the agronomic rate of

Table 4 Nitrate-N (NO$_3^-$-N) distribution in the soil profile (0–150 cm) in autumn 2004 with liquid hog manure (LHM—Experiment 1) treatments at Dixon, Saskatchewan

Treatment	Nitrate-N (kg N ha^{-1}) in soil depths (cm)			
	0–60	60–90	90–120	120–150
Control	7	2	2	8
37,000 L ha^{-1} injected yr^{-1}	10	5	8	10
74,000 L ha^{-1} injected yr^{-1}	104	57	27	11
148,000 L ha^{-1} injected yr^{-1}	440	178	53	23
112 kg N ha^{-1} urea yr^{-1}	71	42	16	12
LSD$_{0.10}$	109	24	23	11

LHM (37,000 L ha^{-1} yr^{-1}) did not elevate soil NO$_3^-$-N at any depth compared to the control, and showed less migration with depth compared to the urea fertilizer. This indicated that using agronomic rates of LHM to meet crop N requirements would result in less N leaching compared to urea fertilizer over time.

In contrast to the Dixon LHM site, the Dixon SCM site showed no significant effect of manure addition on soil profile NO$_3^-$-N as related to manure application rate (Table 5). Although not significant, there was an increase in NO$_3^-$-N levels at the 30 Mg ha^{-1} yr^{-1} rate compared to other

Table 5 Nitrate-N (NO$_3^-$-N) distribution in the soil profile (0–150 cm) in autumn 2004 with solid cattle manure (SCM—Experiment 2) treatments at Dixon, Saskatchewan

Treatment	Nitrate-N (kg N ha^{-1}) in soil depths (cm)			
	0–60	60–90	90–120	120–150
Control	15	3	5	6
7.6 Mg ha^{-1} broadcast-incorporated yr^{-1}	16	3	5	7
15.2 Mg ha^{-1} broadcast-incorporated yr^{-1}	14	4	4	5
30.4 Mg ha^{-1} broadcast-incorporated yr^{-1}	24	6	9	15
112 kg N ha^{-1} urea yr^{-1}	44	26	26	31
LSD$_{0.10}$	27	21	21	20

treatments, which was present at all soil depths. The 112 kg N ha^{-1} yr^{-1} urea rate consistently had higher residual NO$_3^-$-N levels with increasing soil depth. Solid cattle manure is largely composed of straw bedding and the additional C promotes net immobilization processes (Chantigny et al. 2001). This provided a slow release of plant available N that was quickly utilized as mineralization occurred during the growing season, and explained the small residual NO$_3^-$-N levels compared to the urea fertilizer or LHM. Residual NO$_3^-$-N was very low in the surface soil, which indicated that the majority of the N applied in large rates of SCM was immobilized and at a reduced leaching risk.

Melfort and Plenty sites

At Melfort only the 0–60 cm and 60–90 cm soil depths were sampled because of sampling difficulties at the 90–120 cm and 120–150 cm depths. In the 0–60 cm depth the 37,000 L ha^{-1} rate of LHM applied annually and the 111,000 L ha^{-1} of LHM applied once every 3 years showed an increasing trend in residual NO$_3^-$-N compared to the control, but it was not significantly different. At the 60–90 cm depth there was no difference in residual NO$_3^-$-N between the control and LHM treatments. The urea treatment had significantly greater NO$_3^-$-N at both soil depths compared to the control and LHM, reflecting enhanced mobility in the soil profile as urea was rapidly converted to NH$_4^+$-N, followed by nitrification to NO$_3^-$-N. Qian and Schoenau (2002) estimated that between 60 and 80% of N in LHM was either readily available as inorganic N or was mineralized over the growing season, with the rest of the N remaining as organic N. Mooleki et al. (2002) found that the residual NO$_3^-$-N effects from LHM were shorter on soils with greater organic matter and greater annual precipitation because of leaching, gaseous losses and immobilization processes.

At the Plenty site, the residual NO$_3^-$-N levels (0–60 cm depth) for the LHM treatments were very large (>500 kg NO$_3^-$-N ha^{-1}) and NO$_3^-$-N increased significantly in the order of: control < urea fertilizer (40 kg N ha^{-1} yr^{-1}) < agronomic rate of LHM (37,000 L ha^{-1} yr^{-1}) << twice the agronomic rate of LHM (74,000 L ha^{-1} yr^{-1}).

The soil NO$_3^-$-N at the 74,000 L ha^{-1} yr^{-1} rate of LHM, in the 0–60 cm depth, was much larger than soil NO$_3^-$-N under LHM application at the other two sites. Heavy clay soils can cause plant nutrients to become stratified near the soil surface (Morrison and Chichester 1994). The large amounts of nitrate in the 0–60 cm depth of the agronomic rate of LHM (584 kg NO$_3^-$-N ha^{-1}) and twice the agronomic rate of LHM (1,112 kg NO$_3^-$-N ha^{-1}) treatments may be of concern, because the heavy clay soils displayed vertisolic characteristics in dry conditions, which can promote rapid water infiltration via macropore flow during heavy precipitation events. This could potentially transfer large amounts of residual NO$_3^-$-N at the soil surface to greater soil depths very quickly. Thus, even heavy clay soils that normally have lower NO$_3^-$-N leaching losses, have the potential to accumulate large amounts of NO$_3^-$-N at depth.

Results from the Plenty site show that NO$_3^-$-N movement in the heavy clay was not confined to the surface soil, and the 74,000 L ha^{-1} yr^{-1} rate of LHM was significantly higher (109 kg NO$_3^-$-N ha^{-1}) than the 37,000 L ha^{-1} yr^{-1} rate of LHM (50 kg NO$_3^-$-N ha^{-1}) in the 60–90 cm depth. At the 90–120 cm and 120–150 cm depths the residual NO$_3^-$-N differences between treatments became much smaller.

Conclusions

Nitrate-N loss under manure management can become an issue if residual soil NO$_3^-$-N accumulates over time. Excess NO$_3^-$-N is susceptible to loss mechanisms such as leaching and denitrification, and by balancing N inputs and outputs to meet, but not exceed crop requirements, environmental contamination can be minimized.

Agronomic rates of LHM and SCM (37,000 L ha^{-1} yr^{-1} LHM and 7.6 Mg ha^{-1} yr^{-1} SCM), or larger rates of LHM (111,000 L ha^{-1} yr^{-1}) applied once every 3 years did not result in large amounts of apparent N loss. Twice and four times the agronomic rate of LHM each year caused NO$_3^-$-N elevation in the surface soil (0–60 cm). Reduced application frequency of the large rates, as at Melfort, also limited NO$_3^-$-N accumulation. Drought conditions and crop

failure resulted in greater residual NO_3^--N, as at Plenty. Results from the Plenty and Dixon site both indicated that at larger rates of LHM, there was significant deep leaching of NO_3^--N below 60 cm. These results emphasize the need for LHM application to meet but not exceed crop N requirements, to avoid potential deep migration of NO_3^--N below the rooting zone where it is difficult to recover in future cropping seasons. Climatic conditions that reduce crop yield and N removal potential will require reduced rates and frequency of manure application to avoid loading.

Agronomic rates of SCM resulted in reduced NO_3^--N in the surface soil (0–60 cm), because its large C:N ratio caused net immobilization with initial incorporation. Net immobilization and greater volatilization losses with SCM broadcast and incorporation resulted in lower plant availability at agronomic rates. Twice and four times the agronomic rate of SCM had NO_3^--N amounts equivalent to an agronomic application of LHM in the surface soil (0–60 cm). Nitrate-N leaching does not appear to be an issue with larger rates of SCM in the first few years of application.

In conclusion, LHM and SCM applied at agronomic rates (37,000 L ha^{-1} yr^{-1} and 7.6 Mg ha^{-1} yr^{-1}, respectively) that matched crop requirements over the growing season did not increase residual NO_3^--N levels in the soil profile over time. Only at large (excessive) rates of LHM was there evidence of significant NO_3^--N loading in the surface soil (0–60 cm) and leaching below 60 cm, to cause significant loss of N.

References

Brinton WF (1985) Nitrogen response of maize to fresh and composted manure. Biol Agric Hortic 3:55–64

Chang C, Entz T (1996) Nitrate leaching losses under repeated cattle feedlot manure applications in southern Alberta. J Environ Qual 25:145–153

Chantigny MH, Rochette P, Angers DA (2001) Short-term C and N dynamics in a soil amended with pig slurry and barley straw: A field experiment. Can J Soil Sci 81:131–137

Chang C, Janzen HH (1996) Long-term fate of nitrogen from annual feedlot manure applications. J Environ Qual 25:785–790

Gehl RJ, Schmidt JP, Stone LR, Maddux LD (2004) Quantifying nitrate leaching in sandy soils as affected by N and water management, vol 10. In: Schlegel AJ (ed), Proceedings of Great Plains Soil Fertility Conference. Kansas State University, 2–3 March, 2004, Denver, Colorado, U.S.A., pp 4–7

Keeney DR (1982) Nitrogen management for maximum efficiency and minimum pollution. In: Stevenson FJ (ed) Nitrogen in Agricultural Soils. Agron. Monogr. 22. ASA, CSSA and SSSA, Madison, WI, U.S.A., pp 605–649

Keeney DR, Nelson DW (1982) Nitrogen—inorganic forms. In: Page AL, Miller RH, Keeney DR (eds) Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. Agron. Monogr. 9. ASA and SSSA, Madison, WI., U.S.A., pp 643–698

Mooleki SP, Schoenau JJ, Hultgreen G, Wen G, Charles JL (2002) Effect of rate, frequency and method of liquid swine manure application on soil nitrogen availability, crop performance and N use efficiency in east-central Saskatchewan. Can J Soil Sci 82:457–467

Mooleki SP, Schoenau JJ, Charles JL, Wen G (2004) Effect of rate, frequency and incorporation of feedlot cattle manure on soil nitrogen availability, crop performance and nitrogen use efficiency in east-central Saskatchewan. Can J Soil Sci 84:199–210

Morrison JE, Chichester FW (1994) Tillage system effects on soil and plant nutrient distributions on vertisols. J Prod Agric 7:364–373

Paul JW, Beauchamp EG (1994) Short-term nitrogen dynamics in soil amended with fresh and composted cattle manures. Can J Soil Sci 74:147–155

Qian P, Schoenau JJ (2000) Use of ion exchange membrane to assess soil N supply to canola as affected by addition of liquid swine manure and urea. Can J Soil Sci 80:213–218

Qian P, Schoenau JJ (2002) Availability of nitrogen in solid manure amendments with different C:N ratios. Can J Soil Sci 82:219–225

SAS Institute Inc (1985) SAS user's guide. Statistics, Version 5, ed. SAS Institute Inc. Cary, NC, U.S.A

Schoenau JJ, Bolton K, Panchuk K (2000) Managing Manure as a Fertilizer. Farm Facts. Publ. SUS-MMF1100. Saskatchewan Agriculture and Food, Regina, Saskatchewan, Canada

Schoenau JJ, Mooleki SP, Malhi SS, Hultgreen G (2004) Strategies for maximizing crop recovery of nutrients applies as liquid swine manure, vol 10. In: Schlegel AJ (ed) Proceedings of Great Plains Soil Fertility Conference. Kansas State University. 2–3 Mar. 2004. Denver, Colorado, U.S.A., pp 8–14

Technicon Industrial Systems (1973) Ammonia in acid digest. Industrial Method No. 325-74W. Technicon Industrial Systems, Tarrytown, NY

Thomas RL, Sheard RW, Moyer JR (1967) Comparison of conventional and automated procedures for nitrogen, phosphorus, and potassium analysis of plant material using a single digestion. Agron J 59:240–248

Weil RR, Weismiller RA, Turner RS (1990) Nitrate contamination of groundwater under irrigated coastal plain soils. J Environ Qual 19:441–448