Soil mineral nitrogen responses following liquid hog manure application to semiarid forage lands

E. W. Bork[1], B. D. Lambert[2], S. Banerjee[3], and L. J. Blonski[4]

[1]*Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, Alberta, Canada T6G 2P5 (e-mail: Edward.bork@ualberta.ca);* [2]*Alberta Environment and Sustainable Resource Development, Edmonton, Alberta, Canada T5K 2J6;* [3]*Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada T6G 2H1; and* [4]*Range Branch, Ministry of Forests, Lands and Natural Resource Operations, Prince George, British Columbia, Canada V2N 4W5.* *Received 7 January 2013, accepted 24 April 2013.*

Bork, E. W., Lambert, B. D., Banerjee, S. and Blonski, L. J. 2013. **Soil mineral nitrogen responses following liquid hog manure application to semiarid forage lands**. Can. J. Soil Sci. **93**: xxx–xxx. Expansion of intensive livestock operations into semiarid regions lacking cultivated lands requires consideration of perennial forages for the efficient and sustainable disposal of manure. Little information exists on the nutrient dynamics associated with the application of manure to these areas. We examined soil mineral nitrogen (N) responses in four sites of the mixed-grass prairie, including two native grasslands and two introduced pastures, following different seasons (fall vs. spring), methods (dribble broadcast vs. coulter injected) and rates of liquid hog manure application (9.4, 18.8, 37.5, 75 and 150 kg ha^{-1} available N). Soil mineral N, including NO_3-N, NH_4-N and total mineral N, were assessed after application but prior to plant growth in April 1999, and again one growing season later in April 2000. Initial soil N did not vary with season of application. Soil mineral N predictably increased with application rate, but only in the upper soil profile (0–20 cm). Decreases in soil mineral N after one growing season in all treatments highlighted the ability of these perennial forage lands to immobilize large amounts of soil N, a significant portion of which was related to N uptake by vegetation. Compared with broadcast application, manure injection led to 35% greater soil mineral N (both NO_3 and NH_4) prior to plant growth, a response that persisted 1 yr later (+12%), thus demonstrating the N conserved benefits of manure incorporation. Overall, increases in soil mineral N within these forage lands appeared to be relatively short-term in nature, largely depleting over the course of a single growing season, suggesting one-time liquid hog manure application at low to moderate rates may be sustainable in this region of the mixed-grass prairie.

Key words: Coulter injection, introduced pasture, liquid hog manure, mineral nitrogen, native grassland, nitrogen recovery

Bork, E. W., Lambert, B. D., Banerjee, S. et Blonski, L. J. 2013. **Réaction de l'azote minéral du sol après épandage de lisier de porc dans des prairies semi-arides**. Can. J. Soil Sci. **93**: xxx–xxx. L'expansion de l'élevage intensif dans les régions semi-arides où l'on cultive peu les terres exige qu'on envisage le recours aux vivaces fourragères pour un épandage efficace et durable du fumier. Malheureusement, on sait peu de choses sur la dynamique des éléments nutritifs associée à l'application de fumier sur de tels sols. Les auteurs se sont intéressés à la réaction de l'azote minéral (N) du sol à quatre endroits des prairies mixtes, notamment deux prairies indigènes et deux pâturages artificiels, à diverses saisons (automne c. printemps) et pour différentes méthodes d'épandage (liquide à la volée c. incorporation à la herse) et pour différents taux d'application du lisier de porc (9,4, 18,8, 37,5, 75 et 150 kg de N disponible par hectare). La concentration de N minéral dans le sol, qui incluait le N-NO_3, le N-NH_4 et le N minéral total, a été évaluée après application du lisier, mais avant la croissance des plantes en avril 1999, puis une période végétative plus tard, en avril 2000. La concentration de N initiale dans le sol ne varie pas avec la saison d'application. Comme on pouvait le prévoir, la teneur en N minéral du sol augmente avec le taux d'application, mais uniquement dans la partie supérieure du profil (0–20 cm). La baisse de la concentration de N minéral dans le sol après une période végétative, peu importe le traitement, fait ressortir la capacité des vivaces fourragères à immobiliser une grande quantité de N dans le sol, une part importante de ce dernier se retrouvant dans la végétation. L'incorporation du lisier par injection ajoute 35 % plus de N minéral (sous forme de NO_3 et de NH_4) au sol que l'épandage à la volée liquide avant la croissance des plantes, et la réaction persiste un an plus tard (+12 %), illustration des avantages durables de l'incorporation du fumier sur le plan de la conservation du N. Dans l'ensemble, l'augmentation de la concentration de N minéral dans les terres fourragères semble relativement de courte durée, et disparaît dans une large mesure durant la même période végétative, ce qui laisse croire qu'une légère à moyenne application de lisier de porc pourrait s'avérer une pratique durable dans cette région des prairies mixtes.

Mots clés: Incorporation à la herse, pâturages artificiels, lisier de porc, azote minéral, prairie indigène, récupération de l'azote

Many livestock industries in North America have transitioned to increased confinement feeding (called intensive livestock operations, or ILOs) and greater animal concentrations (Jackson et al. 2000; Cunningham et al. 2005;

Abbreviations: **CWG**, crested wheatgrass; **FG**, fescue grassland; **ILO**, intensive livestock operation; **LHM**, liquid hog manure; **MB**, meadow brome; **MG**, mixed grassland

Gunderson 2011). These changes have arisen from the need for economies of scale, cost control and increasing regulations aimed at reducing pollution associated with livestock production, the latter of which reflects the public's growing concern and awareness for environmental safety (Jongbloed and Lenis 1998). Increases in the number and size of ILOs across western Canada have led to the establishment of large-scale hog production facilities within relatively unpopulated semi-arid regions (Canada–Alberta Environmentally Sustainable Agriculture Agreement 1991). Such geographic shifts may limit conflict over aesthetics and odor, but create new challenges, including the disposal of animal wastes such as liquid hog manure (LHM). Manure disposal must be done so as to not contribute to soil, water or air pollution, while remaining compatible with efficient crop production (Evans et al. 1977).

Traditional sinks for LHM in the Canadian prairies have been relatively productive cultivated lands, which are not always available in semi-arid regions. Given that it is unrealistic to transport liquid manure over long distances, alternative lands are being considered for manure disposal to maintain cost-effectiveness. Although potentially less productive, perennial forage lands, including native grasslands and introduced pastures, are often widely available adjacent to these operations and could provide an alternative sink for LHM disposal. Moreover, manure application can benefit forage crops through increased production and forage quality (Gangbazo et al. 1999; Blonski et al. 2004).

Most previous studies have assessed varying rates of manure addition for altering production on cultivated lands (e.g., Schmidt et al. 2000, 2001), with fewer studies exploring the same aspects on perennial forage crops (Lowrance et al. 1998; Bittman et al. 2005; Bell et al. 2006; Van Vliet et al. 2006) or annual crops intended for forage (Gangbazo et al. 1995, 1999). Furthermore, almost all of those studies on forage lands have generally been done under moist conditions favorable for plant growth (e.g., Bittman et al. 2005; Van Vliet et al. 2006). In contrast, little information exists on the effect of manure addition to native grassland soils, particularly in semi-arid regions, except those that have examined responses to cattle manure (Power and Alessi 1971; Stavast et al. 2005; Bell et al. 2006).

Liquid hog manure application to native grassland has been associated with relatively short-term, temporary changes in plant composition (Bork and Blonski 2012). As native grasslands are typically situated in semi-arid regions where plant growth is limited by moisture rather than nutrients (Willms and Jefferson 1993), high manure rates may lead to larger and prolonged increases in soil nutrient availability, including soil mineral nitrogen (N). Elevated soil nutrients may increase the risk of movement of nutrients applied as manure into and through the soil profile, highlighting the need to examine soil nutrient responses within forage lands following LHM application.

Manure addition to introduced pasture and native grassland is typically limited to surface applications with little to no incorporation, with most previous investigations on manure application techniques done in cultivated soils (Sawyer et al. 1990). While some investigations have compared methods of manure incorporation (i.e., injection) to introduced pasture (Lory et al. 1995), no information exists on the effects of LHM application methods (injected vs. broadcast) to previously uncultivated native grasslands of the Canadian prairies. Where manure disposal on perennial grassland is contemplated, an understanding is needed on the effects of different application methods and rates on soil nutrient dynamics (Sawyer et al. 1990). This information has the potential to influence the management of ILOs and ongoing regulation of these operations (Neeteson 2000), and becomes a greater concern for publicly managed rangelands with a mandate for multiple uses, including resource conservation.

The objective of this research was to assess soil mineral N following LHM application to semi-arid forage lands in the mixed-grass prairie. Specific objectives included the evaluation of soil mineral N, both temporally (i.e., short-term depletion) and spatially (i.e., variation with soil depth) under: (1) varying LHM application rates, (2) different application methods (broadcast vs. sub-surface injected), and (3) different seasons of application (fall vs. spring). A secondary objective was to compare mineral N dynamics between native grassland and introduced pasture, as well as relate N recovery in above-ground forage to observed changes in soil mineral N among perennial forage types.

MATERIALS AND METHODS

Study Area and Design

Manure treatments were conducted on four perennial grasslands (two introduced pastures and two native grasslands) near Little Fish Lake, 40 km east of Drumheller in south-central Alberta (lat. 51°22′N, long. 112°13′W). The study area is located in the northern mixed-grass prairie (Strong and Leggat 1992), where native grasslands are abundant but interspersed by introduced pasture. The area has a continental climate, with warm summers and cool winters, and a long-term semi-arid mean annual precipitation of 394 mm. Precipitation during the growing season (May to August) in 1999 following LHM application was 284 mm, 30% above normal.

The four study sites represent a range of common soil and growing conditions in Alberta. The two native grasslands were a mixed grassland (MG) containing a xeric *Stipa–Agropyron* community, and a mesic fescue grassland (FG) containing a *Festuca–Stipa* community (Coupland 1961). The two introduced pastures were a 2-yr old mesic meadow bromegrass (MB) (*Bromus riparius* Roem & Schult) and a 15-yr old xeric crested wheatgrass (CWG) (*Agropyron cristatum* L.) sward.

Both introduced pastures contained low to moderate amounts of alfalfa (*Medicago sativa* L.). Soil characteristics at each site in 1998 prior to LHM application are provided in Table 1.

Manure treatments at each site were established using a randomized block design. Each site was internally uniform with respect to physical conditions (e.g., slope, aspect, and topographic position) and initial vegetation, and established on vegetation in good to excellent condition. Each site measured 150 by 35 m and was fenced after treatment to exclude livestock to avoid confounding vegetation responses and manure treatments, with grazing permitted in late summer to avoid excess litter accumulation (Blonski et al. 2004).

Twenty plots, each 6×35 m in size, were established at each site ($N = 80$ total). Ten randomly applied treatments consisted of combinations of five different target rates (10, 20, 40, 80, and 160 kg ha^{-1} NH_4-N) of LHM applied during the fall of 1998 (Oct. 05–07), using either of two application methods (surface and injection). The other 10 plots received the same five rates and two methods, but were applied the following spring (1999 Apr. 12–13). Fall treatments were conducted after plant growth ceased, while spring treatments were done immediately after spring thaw but prior to green up.

Manure Application

Manure was applied using a 3-m-wide GreenTrac injection unit, consisting of a pressurized tank with a distributor that delivered LHM through hoses to injector shanks directly behind single vertical coulters spaced 25 cm apart. When injecting, applicator shanks penetrated 7.5–10 cm into the soil. For surface application, coulters were raised 10–20 cm above the ground and manure top-dressed. Applicator speed and orifice diameters within the distributor were adjusted to vary application rates, with pre-treatment manure sampling and calibration used to determine necessary speeds. A 1-m non-treated buffer strip was maintained between plots.

Preliminary samples of LHM were collected from the source lagoon and analyzed for nutrient content to derive appropriate bulk volume application rates. Final manure application volumes, adjusted for N concentrations, led to minimal variation in actual N rates between seasons, which ranged from 9.4 to 150 kg ha^{-1} N. Given that the 10 kg ha^{-1} rate could not be obtained under normal operating conditions due to an excessive machine speed requirement, this rate was achieved by diluting manure with water in a 1:1 mix. Thus, manure application volumes across treatments ranged from 13 000 to 107 000 L ha^{-1} in the fall, and from 11 000 to 84 000 L ha^{-1} in the spring (Blonski et al. 2004).

The LHM was sourced from the first of a three-pit, non-agitated, uncovered lagoon of a 4000-sow hog operation. Analysis of the LHM prior to treatment indicated a mean moisture content of 99.3% in both fall and spring. Concentrations of NH_4-N during the fall were 0.17%, but increased to 0.21% in spring. Manure concentrations of NO_3-N and organic-N during both fall and spring were each less than 0.01%. Manure pH values were 7.4 to 7.7, while the electrical conductivity ranged from 14.7 to 17.6 dS m^{-1}.

Hog manure varies in composition, depending on manure age, dilution level, nature of the storage facility, and odor treatment (O'Dell et al. 1995). As a result, manure was consistently taken from the same place near the center of the lagoon using an intake hose suspended from a float that allowed the hose opening to extract LHM from 1-m below the lagoon surface. During application, samples were collected from each truckload of manure applied to plots. Subsequent testing indicated all loads were consistent for moisture, EC, pH, organic-N, NO_3-N, and NH_4-N.

Soil Sampling

Initial baseline soil characteristics at each study site were assessed in October 1998 using five randomly located soil cores extracted to 20 cm soil depth. Samples were composited by site and evaluated for various parameters (Table 1). Initial total soil mineral N was relatively low

Table 1. Summary of mean (±SD) soil characteristics in the 0–20 cm depth for each of the study sites sampled in September 1998, prior to manure application

	Native grassland		Introduced pasture	
Constituent[z]	Mixed grassland	Fescue grassland	Crested wheatgrass	Meadow brome
NH_4-N (mg kg^{-1})	1.22 (0.72)	1.26 (0.54)	1.52 (0.77)	1.14 (0.37)
NO_3-N (mg kg^{-1})	0.72 (0.66)	0.22 (0.22)	2.96 (2.15)	2.94 (1.11)
EC[z] (dS m^{-1})	0.34 (0.16)	0.12 (0.03)	0.56 (0.41)	0.13 (0.022)
pH	6.6 (0.2)	6.3 (0.2)	7.0 (0.7)	6.6 (0.2)
OM[z] (%)	3.86 (0.67)	4.94 (1.22)	3.22 (0.82)	3.22 (0.97)
Db[z] (Mg kg^{-3})	1.28 (0.04)	1.09 (0.03)	1.28 (0.08)	1.28 (0.14)
Texture	Loam	Loam	Loam	Sandy loam
Moisture regime	Xeric	Mesic	Xeric	Mesic
Soil type	Dark Brown Chernozem	Black Chernozem	Dark Brown Chernozem	Dark Brown Chernozem

[z]EC, electrical conductivity; OM, organic matter; Db, bulk density.

at the MG (1.94 mg kg^{-1}) and FG (1.48 mg kg^{-1}) sites, and generally greater at the CWG (4.48 mg kg^{-1}) and MB (4.08 mg kg^{-1}) sites due to elevated soil NO_3-N.

Soil samples were subsequently collected within each of the 80 plots at two time periods, 1999 Apr. 16–18, after fall and spring manure applications were complete but prior to plant growth, and again 2000 Apr. 21–22, 12 mo later (after spring thaw) to assess residual soil mineral N one full growing season after treatment. During sampling, 10 soil cores, each 2.5 cm in diameter by 40 cm deep, were randomly taken within each plot inside of a 50-cm buffer zone around the plot perimeter. Individual cores were separated into shallow (0–20 cm) and deep (20–40 cm) soil layers, and subsequently composited for each depth class within each plot for further analysis.

Soil samples were prepared using methods from Nyborg et al. (1992). Samples were air dried at 25–30°C, sieved and ground through a 1-mm screen, and subsequently stored in airtight plastic bags. All soil samples were later extracted for NH_4-N [exchangeable] and NO_3-N [water soluble] using a 2M solution of potassium chloride (McKeague 1978), and the concentrations in the aqueous extracts determined using a continuous flow analyzer (Technicon Autoanalyzer II, Folio Instruments Inc., Kitchener, ONT.).

Removal of Nitrogen by Vegetation

Representative vegetation samples were harvested from two randomly located 0.25-m^2 quadrats in each plot during the summer of 1999 at peak growth in late July. Samples were sorted by plant growth form (grass and forb), oven-dried at 60°C to constant mass and weighed, and subsequently ground through a 1-mm Wiley mill. Ground samples were tested for plant N concentration using a LECO FP-428 nitrogen determinator (Lee et al. 1996). Total N removed in each plot was derived by the determination of total herbage N yield, assessed as the sum of the products of total biomass (kg ha^{-1}) and the specific concentration of N for each growth form (see Blonski et al. 2004).

Statistical Analysis

Prior to analysis, all data (NH_4-N, NO_3-N and total soil mineral N) were checked for normality and homogeneity of variances using Shapiro–Wilks and Levene's tests, respectively. No transformations were necessary. Prior to testing main effects, the role of forage type (native grassland vs. introduced pasture) in altering aggregate (0–40 cm) soil NH_4-N, NO_3-N and total mineral N was assessed using a contrast between sites: sites were random in this analysis with plots nested within sites.

As total soil mineral N values after manure application but prior to plant growth were similar among forage types and sites, subsequent mixed model analysis of variance (ANOVA) was performed for a split-plot experimental design to evaluate soil N responses to the fixed effects of season, method and rate of LHM application (whole plot), as well as depth of sampling (sub-plot), with blocks (i.e., sites) random. Significance for all main effects and their interactions was set at $P < 0.05$. For LHM rate, contrasts were performed to assess the specific effect (e.g., linear vs. quadratic responses) of rate.

Finally, changes in total soil mineral N (i.e., N depletion) from 1999 to 2000 were correlated with N removed in herbage biomass during the interceding growing season [see Blonski et al. (2004) for detailed responses on N removal]. This assessment was done separately for each study site, with all available soil N depletion values converted to kilograms per hectare using mean bulk densities for each site and soil depth layer.

RESULTS

Soil Nitrogen Responses to LHM Treatment

No differences in soil mineral N, including total N, NO_3-N and NH_4-N, were observed prior to the 1999 growing season relative to the different seasons of LHM application (Table 2). Similar results were evident in spring 2000, although total soil mineral N in 2000 (15.1–16.2 mg kg^{-1}) was generally lower than the year prior (24.0–24.5 mg kg^{-1}).

Method of LHM application affected total soil mineral N in April 1999, largely due to changes in soil NO_3-N (Table 2). Method also interacted with depth to alter NO_3-N, NH_4-N, and total mineral N at that time. Soils receiving LHM through injection were greater in NO_3-N and NH_4-N (and thus total mineral N) relative to broadcast treatments, but only in the top 20 cm of soil (Table 3). No soil mineral N responses were observed relative to application method below 20 cm soil depth, with soil N values generally lower ($P <$ 0.0001) below 20-cm depth (e.g., mean total mineral $N = 5.6 \pm 0.8$ mg kg^{-1}) than at the soil surface (e.g., mean total mineral $N = 18.7 \pm 0.8$ mg kg^{-1}). Overall, total soil mineral N in April 1999 was 35% greater within injected plots compared to those receiving broadcast applications of LHM.

One full growing season later, total soil mineral N and NO_3-N continued to be affected by the method of LHM application, as well as by a method × depth interaction (Table 2). Total soil mineral N remained greater (+12%) in plots previously receiving injection of manure rather than broadcast application (Table 3). However, this increase was attributed solely to the availability of soil NO_3-N, and again only in the top 20 cm of soil.

Application rate significantly impacted soil mineral N, but only in 1999 (Table 2). Moreover, interactions of rate with soil depth were observed on soil NO_3-N, NH_4-N, and total mineral N. Not surprisingly, application of increasing N within LHM led to greater soil NO_3-N (Fig. 1a) and NH_4-N (Fig. 1b) during the spring of 1999 in the top 20 cm of soil, with the greatest

Table 2. Summary of ANOVA F-values on the effects of various liquid hog manure LHM treatments on soil NO_3-N, NH_4-N and total soil mineral N, as measured in April 1999 and April 2000

	1999 (prior to plant growth)			2000 (after one growing season)		
Factor	NO_3-N	NH_4-N	Total N	NO_3-N	NH_4-N	Total N
Rate	7.42***	13.3***	32.2***	0.58	0.96	0.90
Linear	28.2***	51.8***	128.0***	0.22	3.22	1.94
Quadratic	0.87	1.15	0.01	0.62	0.27	0.90
Method	5.58*	2.35	12.5***	3.85*	0.01	2.82
Season	0.22	0.05	0.06	0.47	0.91	1.22
Rate × Method	0.57	0.71	1.78	0.45	0.44	0.49
Rate × Season	0.06	2.10	2.20	1.20	1.20	1.30
Method × Season	0.03	2.04	1.25	0.79	0.49	0.12
Rate × Method × Season	0.03	0.53	0.34	0.86	1.19	0.70
Depth	69.0***	60.7***	165.8***	62.5***	124.6***	163.0***
Depth × Rate	4.75**	7.10***	14.6***	0.73	1.47	1.17
Depth × Method	9.22**	3.55*	14.8***	5.20*	0.77	6.10*
Depth × Season	2.48	0.31	2.62	0.42	0.64	0.97
Depth × Rate × Method	0.81	0.35	1.16	0.41	0.71	0.48
Depth × Rate × Season	0.62	0.37	0.20	1.65	0.67	2.30
Depth × Method × Season	0.43	0.81	0.11	1.01	0.04	0.62
Depth × Rate × Method × Season	0.86	0.06	0.23	0.56	0.88	0.29

*, **, *** Indicates significant *F*-values at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

concentrations under the 75 and 150 kg ha^{-1} N rates of LHM. In addition, although the primary form of mineral N applied in LHM was NH_4-N (>95%), the proportion of total soil mineral N comprised of NO_3-N during 1999 was consistently between 44 and 55% across the various LHM rates, a pattern that remained regardless of the time elapsed since manure application (i.e., 6 mo prior in the fall vs. 1 wk earlier in the spring).

Total soil mineral N increased markedly with LHM rate in the spring of 1999 (Fig. 2a). This increase was also observed below 20-cm depth, though only in plots treated with the greatest LHM rate. One year later, little difference in soil mineral N was found between treatments (Fig. 2b).

Amounts of N removed by herbage biomass during the summer of 1999 were positively related to a decrease in total soil mineral N from spring 1999 to spring 2000 within both the introduced pasture (Fig. 3a, b) and native grassland (Fig. 3c, d) study sites. However, stronger relationships were observed for the two

Table 3. Soil mineral N (mg kg^{-1}) in perennial forage swards sampled prior to (1999) and after (2000) one full growing season following different LHM application methods

			Soil sampling depth		
Sampling time	Response	Method	0–20 cm	20–40 cm	Both layers
April 1999	NO_3-N	Injected	11.17*a*	3.00*a*	7.09*a*
		Broadcast	6.79*b*	2.99*a*	4.89*b*
		SE		1.49	1.40
	NH_4-N	Injected	11.28*a*	2.46*a*	6.87*a*
		Broadcast	8.16*b*	2.78*a*	5.47*a*
		SE		1.31	1.17
	Total N	Injected	22.45*a*	5.46*a*	13.96*a*
		Broadcast	14.95*b*	5.77*a*	10.36*b*
		SE		1.09	0.83
April 2000	NO_3-N	Injected	6.03*a*	2.00*a*	4.01*a*
		Broadcast	4.30*b*	2.07*a*	3.18*b*
		SE		0.69	0.64
	NH_4-N	Injected	5.64*a*	2.85*a*	4.25*a*
		Broadcast	5.41*a*	3.03*a*	4.22*a*
		SE		0.29	0.22
	Total N	Injected	11.67*a*	4.85*a*	8.26*a*
		Broadcast	9.71*b*	5.10*a*	7.40*b*
		SE		0.88	0.82

a, *b* Within a year and response variable, column means with different letters differ at $P = 0.05$.

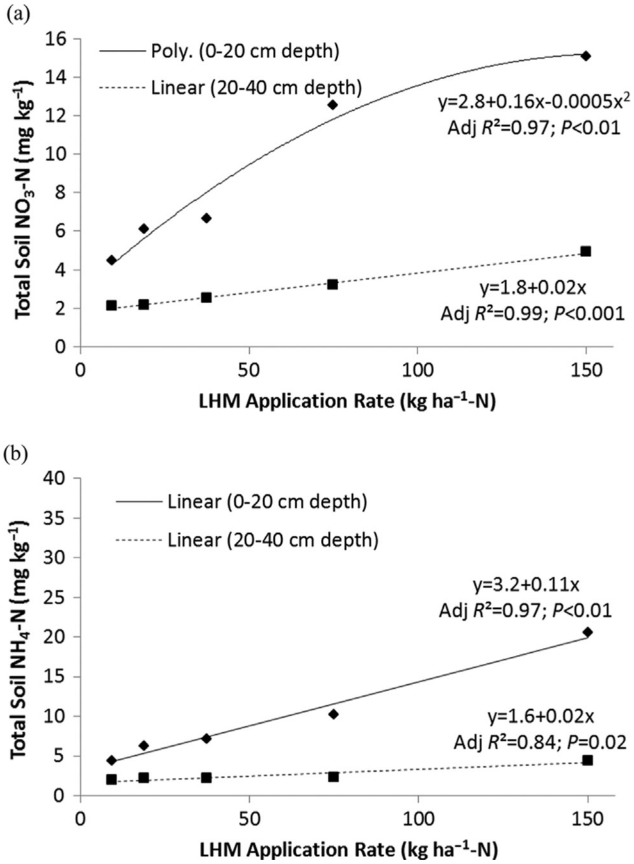

Fig. 1. Variation in (a) soil NO_3-N, and (b) soil NH_4-N, within the shallow and deeper soil layers of perennial forage stands sampled after liquid hog manure application but prior to the growing season.

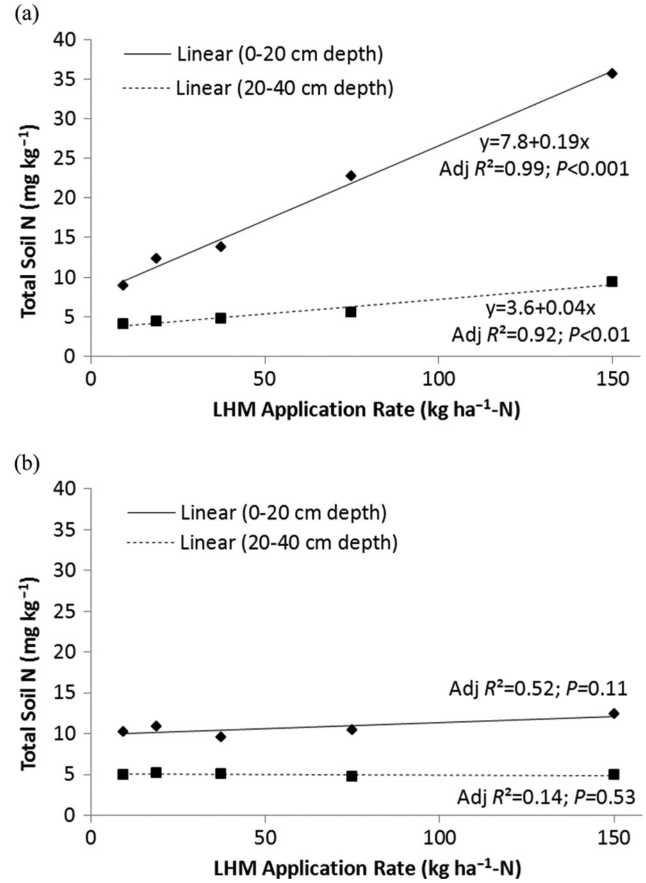

Fig. 2. Total soil mineral nitrogen (NO_3+NH_4) in the shallow (0–20 cm) and deeper (20–40 cm) soil layers sampled (a) after liquid hog manure application but prior to plant growth, and (b) one full growing season later.

introduced pastures (Adj. $R^2=50$–62%; $P<0.0001$) than the native grasslands (Adj. $R^2=26$–43%; $P<0.001$). In addition, within all study sites, plots with low soil N depletion were typically associated with N removal that either met or exceeded expected soil N changes, as exemplified by values above the 1:1 fit line: the opposite was generally observed in plots with high N removal in herbage. Apparent recovery of N in vegetation was particularly high in the CWG site (Fig. 3a) and low in the MG site (Fig. 3c).

Site-based Differences in Soil Nitrogen

Total soil mineral N was similar ($P=0.48$) between introduced pasture (24.9 ± 2.2 mg kg^{-1}) and native grassland (23.7 ± 2.4 mg kg^{-1}) in 1999, although the composition of total mineral N differed between forage types at that time. While native grasslands had more ($P<0.0001$) NH_4-N (15.8 ± 2.1 mg kg^{-1}) than introduced pastures (8.8 ± 0.8 mg kg^{-1}), the latter had greater ($P<0.0001$) NO_3-N (16.1 ± 0.7 mg kg^{-1}) than native grasslands (7.8 ± 0.7 mg kg^{-1}). One year later in 2000, total soil mineral N was slightly lower ($P=0.02$) in native grasslands (14.5 ± 0.8 mg kg^{-1}) than introduced pastures (16.7 ± 0.6 mg kg^{-1}), due primarily to lower NO_3-N (6.2 ± 0.7 mg kg^{-1} vs. 8.2 ± 0.5 mg kg^{-1}, $P=0.01$).

Further examination of individual sites revealed that total soil mineral N at the end of the study was lower ($P<0.05$) in the MG site (11.1 ± 0.5 mg kg^{-1}) compared with all other vegetation types (total mineral N ≥16.1 mg kg^{-1}). The MG soils during 2000 were particularly low in NO_3-N (3.7 ± 0.2 mg kg^{-1}) compared with the others (7.5 ± 0.3 mg kg^{-1}). Mean amounts of N removed in herbage were similar among sites ($P>0.05$), ranging from 15.4 kg ha^{-1} at the MG location to 36.7 kg ha^{-1} in the CWG site.

DISCUSSION

Soil mineral N increased prior to plant growth as rate of LHM increased, which is consistent with previous manure studies (Ledgard et al. 1996; Schmidt et al. 2000). More importantly, these grasslands exhibited depleted soil N after only one growing season, which in turn coincided with high N immobilization in aboveground forage biomass. While these results are consistent with other studies highlighting the importance of

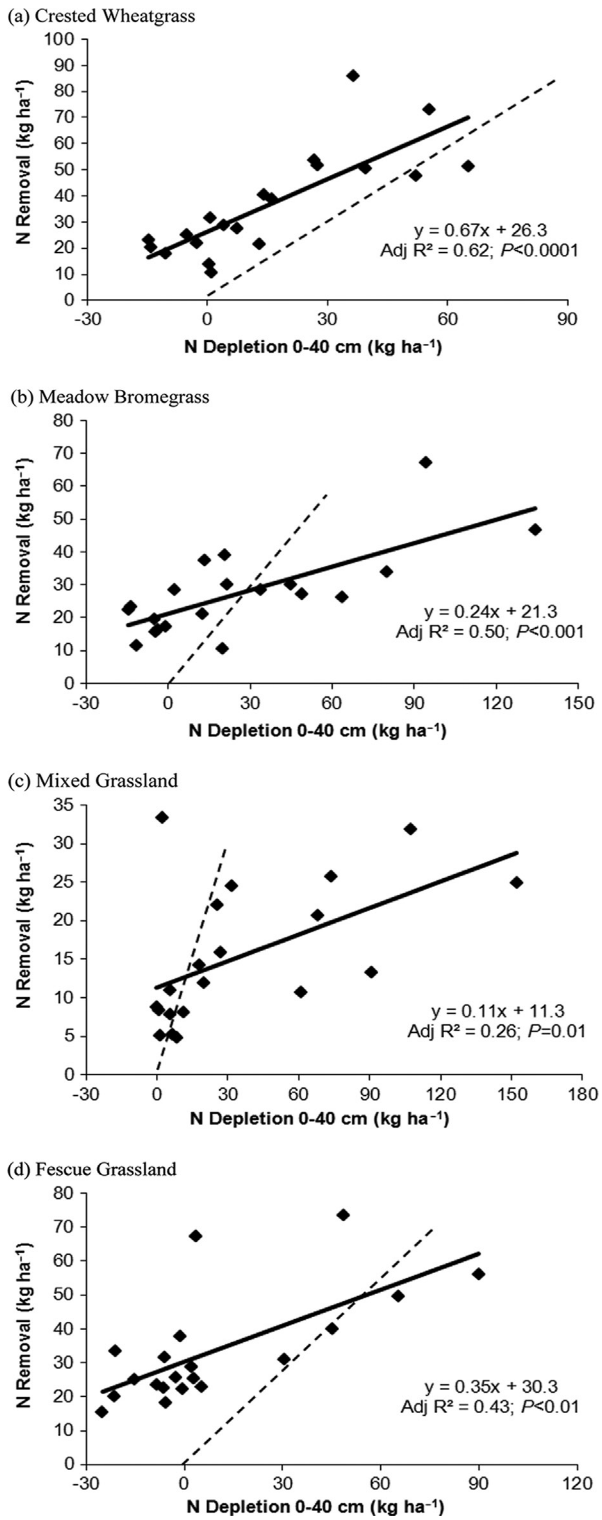

Fig. 3. Relationship between nitrogen (N) removed in aboveground herbage and observed changes in total soil mineral N from April 1999 to April 2000, within the (a) crested wheatgrass, (b) meadow bromegrass, (c) native mixed-grass, and (d) native fescue grassland communities. Dashed lines represent a 1:1 fit.

cover crops in N retention (Cambardella et al. 2010), our results were found in semi-arid grasslands. The high density of fine roots typical of these areas, particularly native grasslands (Coupland and Johnson 1965; Dormaar et al. 1995), likely resulted in favorable uptake of N, which in turn led to little to no apparent carryover of elevated soil N. The rapid depletion of soil mineral N may partly reflect favorable plant growth associated with above-normal rainfall during the 1999 growing season immediately following LHM application. In a parallel investigation, increasing application rates of LHM increased plant biomass, crude protein concentration, and ultimately protein yield within all four study sites during the first growing season following LHM application (Blonski et al. 2004). In addition, they also noted a small positive effect of N addition to protein yield in the second growing season, but this response was limited to plots treated at the greatest LHM rate. Notably, these results closely parallel our findings of elevated soil mineral N within that particular treatment in April 2000. Although plant uptake accounted for a large portion of N removed after LHM application (up to 62%), microbial N immobilization may also have occurred during this time, particularly within the native grasslands where well-developed microbial populations can rapidly sequester nutrients during periods of mineral N abundance (Dormaar and Willms 2000). Moreover, soil N depletion is likely overestimated relative to plant N uptake, as our measures of N depletion reflect an extended period that includes the interval from after forage harvest to April 2000, during which soil N depletion may have continued due to leaching, immobilization and other losses.

Little change in vertical distribution of soil mineral N was detected within the soil profile (i.e., from 0–20 cm to 20–40 cm), either following different seasons (fall vs. spring) of LHM application, or during the first full year after treatment. Moreover, the N distribution profile remained stable despite higher than average rainfall in 1999, which could have increased the risk of mineral N movement, particularly NO_3-N, to deeper (20–40 cm) soil depths. These findings suggest there is minimal risk of N translocation in these soils, presumably because of abundant soil N uptake and immobilization under these conditions. As the lone increase in soil N below 20 cm depth was observed immediately after LHM application, and only under the greatest LHM rate (e.g., 150 kg ha^{-1} NH_4-N), the potential for N movement in these soils appears limited following low to moderate rates of one-time LHM application. Nevertheless, further testing is recommended to determine if this finding consistently occurs under different growing conditions, as lower rainfall could reduce the risk of soil N vertical movement in the profile, but may also reduce plant N uptake, thereby lengthening the time period during which movement could occur.

Although it was anticipated that N immobilization over winter or plant uptake prior to freeze-up may reduce total soil mineral N within the fall treatments relative to spring application (i.e., just prior to rapid plant growth), this did not occur. Furthermore, similar soil N levels occurred among treatments and soil depths despite above-average snowfall (+13%) and precipitation (+20%), and slightly lower mean daily air temperatures (−0.9°C), from October 1998 through April 1999 in the region (i.e., at Craigmyle, AB). Elevated moisture in particular could have increased mineral N transformation or translocation. Instead, the lack of seasonal effects on soil mineral N suggests that LHM application to perennial forage lands may be done at either time, with similar implications for subsequent plant growth the following growing season, a result further supported by observations of similar herbage biomass and crude protein yields in 1999 in response to seasonal LHM application (Blonski et al. 2004). As plant growth in this region may begin shortly after spring soil thaw, the option of fall application may be beneficial in increasing the window for LHM disposal, particularly if applications to growing vegetation are to be avoided to prevent smothering of plants (Stavast et al. 2005). In any case, decisions on when to apply LHM should reflect the relative tolerance of vegetation to disturbance at that time, including any risk of undesirable changes in plant species composition within native grasslands (Bork and Blonski 2012).

Although total soil mineral N was similar between forage types after application but prior to plant growth, the contrasting composition of NO_3-N (greater in introduced pasture) and NH_4-N (greater in native grassland) between forage types warrants explanation. As most of the N in LHM at application consisted of NH_4-N, these results suggest rates of nitrification were inherently greater within introduced forage swards. Introduced pastures had less litter (including organic mulch) and more bare soil, similar to other cultivated grasslands (Rao 1998), which in turn may enhance nitrification by increasing soil temperatures (Stark 1996; Booth et al. 2005). Furthermore, native grasslands had considerably higher soil organic matter content and lower pH, which are conducive to soil denitrification (Knowles 1982; Wallenstein et al. 2006). Thus, denitrification may have been greater in native grasslands, resulting in lower NO_3-N content than within introduced pastures. In contrast, slightly higher pH within introduced pastures may have enhanced soil nitrification by promoting nitrifying communities (Hatzenpichler 2012).

The use of coulter injection increased soil mineral N compared with surface broadcast treatments by as much as 35%, particularly NO_3-N, but only at shallow soil depths. These findings indicate that injection technology has the potential to enhance soil N availability, and likely accounts for greater forage quality (e.g., protein concentrations) following injection (Blonski et al. 2004). Injection has the benefit of both increasing infiltration rates into the soil by placing LHM directly within the soil profile and increasing soil surface area contact, as well as reducing N losses associated with the interception of manure by litter or foliage (Rochette et al. 2008) and ammonia volatilization (Frost et al. 1990; Lambert and Bork 2003). During application of LHM, channels in the soil opened up by the coulters were observed to hold nearly all the manure applied in treatments up to 80 kg ha^{-1} N. Only at the highest rate did LHM exceed coulter furrow size and soil hydraulic conductivity within the injected plots, resulting in manure spilling onto the ground surface outside the furrows. Limiting LHM application volumes and/or increasing coulter depth could alleviate this problem, although many other factors in addition to application method influence N losses including soil and meteorological factors (Sogaard et al. 2002). Bittman et al. (2005) used a combination of mechanical soil perforation (i.e., aeration) and surface banding to reduce manure ammonia losses and improve grass yields. As most of the N in our LHM consisted of NH_4, this could minimize nitrous oxide emissions that are more likely to occur in soils with high soil NO_3-N (Mkhabela et al. 2008), although N_2O losses can be substantial from the oxidation of NH_4 in soils with favorable O_2 levels (Bateman and Baggs 2005). As the loss of N can reach as high as 14% from hog manure (Velthof et al. 2003), incorporation strategies (including aeration) that increase downward movement of mineral N can help conserve soil N (Van Vliet et al. 2006).

The benefits of coulter injection over broadcast application in reducing N loss are most evident in situations where the amount of bare soil is high and infiltration rates are low, such as that observed within introduced pastures (Lambert and Bork 2003). In contrast, losses of N were low in native grasslands, including within broadcast treatments, apparently due to high infiltration of LHM into the well-developed surface mulch layer present at these sites (Bork and Blonski 2012). Finally, increases in residual soil mineral N from injection remained apparent 1 yr after LHM application (see Table 3). This occurred despite favorable plant growth the previous year, and given the similar total N removed in plant biomass during 1999 regardless of application method (Blonski et al. 2004), suggests a key benefit of injection is conserving soil N.

CONCLUSIONS

Expansion of intensive hog production facilities into and within semi-arid regions of Alberta is ongoing. Where cultivated lands, the traditional sink for LHM, do not occur in abundance, alternative disposal methods are being considered, one of which is the use of native grassland and introduced pasture. Our results suggest that while a single application of LHM leads to the expected increase in soil mineral N, the latter promptly declined over the following 12 mo, coincident with favorable increases in N removal through forage growth. Moreover, coulter injection appeared to retain soil N as reflected by increased mineral N, and little evidence was found that inorganic N, including NO_3-N, was moving vertically within the soil profile.

Many challenges exist with integrating modern ILO management with the need to maintain sustainability of agricultural lands (Gunderson 2011). Profit maximization leads livestock producers to the concept of manure management at minimum cost, while remaining below certain ''nuisance'' levels (Fleming et al. 1998). Our results suggest that the integration of hog production, including manure disposal, with ongoing range and pasture management may be feasible within this region of western Canada based on soil N dynamics, particularly when coupled with favorable forage responses (Blonski et al. 2004). Application of modest LHM rates to forage lands could provide a practical option for hog producers to dispose of LHM while providing supplemental soil nutrients for forage production. Access to a large area of perennial forage land would provide greater options regarding the timing, frequency, and rates of LHM application, with even infrequent applications of LHM at low rates likely to meet industry needs to achieve ongoing disposal of LHM. However, more information is needed to understand how repeated applications of LHM or how variation in growing conditions following LHM application may alter long-term dynamics of N, phosphorus and other soil properties.

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