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ORIGINAL ARTICLE

Soil nitrogen mineralization in a soil with long-term history of fresh and composted manure containing straw or wood-chip bedding

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Abstract Long-term effects of fresh (FM) versus composted (CM) beef manure application to barley (*Hordeum vulgare* L.) on potentially mineralizable nitrogen (N_0), and mineralizable nitrogen (N) pools, were evaluated in a clay loam soil in southern Alberta, Canada. A suite of laboratory-based indices were evaluated for prediction of soil N supply. The treatments were three rates (13, 39, 77 Mg ha^{-1} dry wt.) of FM or CM containing either straw or wood-chip bedding, 100 kg N ha^{-1} as inorganic fertilizer, and an unfertilized control. Treatments were fall-applied annually for 8 years (1998–2005). Soil samples (top 15 cm) were collected in spring 2006. The medium and high rates of organic amendment resulted in increases in N_0, and readily (Pool I) and intermediate (Pool II) mineralizable N pools in ranges of 140–355 % compared with the average of the fertilizer and control treatments. Fertilizer application had no significant effect on mineralizable N pools, but increased the mineralization rate constant (k) compared with the control. Application of FM and use of straw bedding resulted in a greater quantity of readily available and intermediate mineralizable N, and also increased the rate of N turn-over as indicated by greater values of k, compared with CM and wood-chip bedding. Among laboratory-based measures of soil N supply, $CaCl_2$–NO_3 ($r^2 = 0.84$) and $NaHCO_3$-205 ($r^2 = 0.79$) were strong predictors of plant N uptake (PNU). Increased soil mineralizable N did not translate into greater barley dry-matter yield or PNU. Composted beef manure and use of wood-chip bedding can be recommended as alternatives to FM and use of straw bedding for barley production is Southern Alberta.

Keywords Barley · Bedding · Compost · Fresh manure · Nitrogen mineralization · Nitrogen uptake · Soil nitrogen supply

Introduction

Improving manure management to benefit both agricultural production and the environment requires a

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thorough understanding of the long-term effects of applied manure on active and stable soil organic nitrogen (SON) fractions. The first consideration when manure is applied as a nutrient source is usually to meet the crop N requirements in the year of application (Wen et al. 2003). However, only a small proportion of the N in solid beef manure is in mineral form (Larney et al. 2006). In addition, the availability of N in solid beef manure is low and in some cases net immobilization may occur following manure application (Helgason et al. 2007). A better understanding of the changes in the size and quality of soil mineralizable N pools under long-term application of manure is critical in optimizing crop yield, quality, and N use efficiency to increase productivity and reduce environmental impacts.

High transportation costs often result in high rates of manure application on agricultural land near livestock operations (Freeze et al. 1999). The traditional role of manure as a nutrient source is diminished in such scenarios, and application rates may exceed that required to meet crop nutrient requirements. High application rates of fresh manure are unsustainable in the long-term, leading to adverse effects on soil (Hao and Chang 2003), water (Chang and Entz 1996; Chang and Janzen 1996) and air quality (Chang et al. 1998). Consequently, the increase in the number and size of feedlots in Alberta, Canada over the past decade has resulted in many producers seeking alternative methods to land apply of raw manure to cropland used for barley and corn silage production (Miller et al. 2009).

Composting is an effective means of reducing manure volume and weight, and also increases the stability and uniformity of the manure (Rynk 1992). In addition, composting can eliminate pathogenic bacteria (Larney et al. 2003), human parasites (Van Herk et al. 2004) and weed seed viability (Larney and Blackshaw 2003). Composting can also influence the composition and availability of N in solid beef manure (Helgason et al. 2007). Bedding is an important input at beef cattle feedlots and cereal straw is commonly used as animal bedding in Alberta, Canada. Wood residuals have been explored as alternative bedding material in recent years due to less availability and high cost of cereal straw. Differences in the C:N ratio and chemical composition of cereal straw and wood residuals can influence the availability of N in fresh and composted manure (Miller et al. 2009) and consequently influence the soil N dynamics following long-term manure application.

The size of the mineralizable N pool in soil is affected by crop management, organic amendment decomposition stage (i.e., fresh vs composted), bedding material and application rate, biotic and abiotic soil characteristics, and environmental factors such as soil temperature and water content (Griffin 2008). While single applications of manure contribute only a small amount to mineralized N in the subsequent year, the combined contributions of organic N from repeated applications can lead to a substantial increase in soil N mineralization potential (Eghball et al. 2002; Flavel and Murphy 2006; Mallory and Griffin 2007). The increased soil N mineralization potential can lead to greater soil N supply and subsequently reduce the need for fertilizer N, or increase risk of excess N losses to the environment (Whalen et al. 2001; Snapp and Fortuna 2003; Sharifi et al. 2011).

In contrast to soil mineral nitrogen (SMN), which is plant available and easy to quantify, the release of N from organic forms is dependent on the mineralization process (Beauchamp 1986). History of organic amendment application can significantly change the nature and release rate of the active organic N fraction. Field-based approaches have been developed for the estimation of soil N supply (SNS) under field conditions (Hassink 1995; Zebarth et al. 2005). While field-based approaches provide measures of the SNS to the crop, they are time consuming and require information measured at crop harvest and therefore cannot be used as a predictor of the SNS in making N fertilizer or manure recommendations (Hassink 1995; Sharifi et al. 2007b). Laboratory-based measures of soil N mineralization that could be used as practical predictors of the SNS for crops in soil with history of organic amendment application have yet to be developed (Hassink 1995; Haney et al. 2001; Sharifi et al. 2011).

The use of a standard laboratory-based method for measuring potentially mineralizable N was first proposed by Stanford and Smith (1972). This method requires 24 weeks aerobic incubation of the samples which makes it time consuming and not practical for routine use. Consequently, recent research has focused on the development of more rapid chemical extraction methods (St. Luce et al. 2011). Encouraging results have been reported for hot (100 °C) KCl (Gianello and Bremner 1986a), phosphate–borate buffer at pH 11.2 (Gianello and Bremner 1986b), direct distillation with NaOH (Sharifi et al. 2009), ultraviolet absorbance of 0.01 *M* $NaHCO_3$ extracts at 205 and 260 nm (Hong et al. 1990; Sharifi et al. 2011), the Illinois Soil N Test for estimating amino sugar N (Williams et al. 2007), microbial biomass C or N (Carter and MacLeod 1987), and particulate organic matter C or N (Willson et al. 2001). Few studies have attempted to quantify the effects of long-term application of manure with contrasting maturity and bedding composition on SON fractions and capacity of soil in supplying N to the crop with a wide variety of laboratory-based methods.

The objectives of this study were to: (1) assess the effects of long-term application of fresh and composted beef manure at 13, 39 and 77 Mg ha^{-1} to forage barley on soil mineralizable N and the SNS at a site located in the Southern Alberta, Canada and (2) evaluate a series of laboratory-based measures of SMN and soil N mineralization potential as predictors of SNS in the field.

Materials and methods

Site description and study design

The field experiment was conducted on a clay loam Dark Brown Chernozemic soil (Typic Haploboroll) at Lethbridge, Alberta (49°38′ N, 112°48′ W). Background soil characteristics of the experimental plots before the first treatment (fall 1998) are reported in Table 1. Climate data were obtained from the local weather station, which is <100 m from the field experiment and are reported in Table 2. Growing degree days was determined from the dates of seeding and harvest, and maximum and minimum daily temperatures during the growing season.

Table 1 Soil chemistry at the experimental site in the fall of 1998 before the first treatment application (from Miller et al. 2004)

Parameter[a]	Value[b]
Soil mineral N (kg N ha^{-1})	58.2 ± 2.2
Available P (kg ha^{-1})	42.6 ± 4.9
Extractable K (kg ha^{-1})	55.7 ± 20.6
pH	8.12 ± 0.01
EC (dS m^{-1})	0.3 ± 0.004
C:N ratio	13 ± 1

[a] Available N (NO_3-N + NH_4-N) and C:N ratio of 0- to 60-cm depth; Available P, extractable K, pH and electrical conductivity (EC) of 0- to 15-cm depth; [b] Mean ± 1 SE. Number of samples = 56 (14 treatment plots × 4 replicates), one composite sample was collected from each block

The experiment was initiated in the fall of 1998 with annual fall application of two manure decomposition stages (FM or CM from beef cattle) with two bedding materials [unchopped barley straw (S) or wood chips (W)] and three application rates [13, 39, or 77 Mg ha^{-1} dry matter] arranged in a factorial randomized complete block design with four replications. In addition, an unfertilized control (CON), and an inorganic fertilizer (IN) treatment consisting of 100 kg N ha^{-1} as NH_4NO_3 (34–0–0) plus 17 kg P ha^{-1} as triple superphosphate (0–46–0) were included. Beef manure application rates in this area range from approximately 13–57 Mg ha^{-1} (dry wt.), with a mean value of 38 Mg ha^{-1} (Miller et al. 2009). Fertilizer recommendations for irrigated barley silage in Alberta are 50–130 kg N ha^{-1} and 15–22 kg P ha^{-1} (Alberta Agriculture and Rural Development 1995). The experimental unit was a plot 6 × 25 m in size.

The wood-chip bedding (Sunpine Forest Products, Sundre, AB, USA) consisted of a mixture of 50 % wood chips, bark, and post peelings, and 50 % fine sawdust. The tree source of the wood chip bedding was a 4:1 mixture of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and white spruce [*Picea glauca* (Moenich) Voss]. Details of the feedlot, pen manure, and bedding material (Miller et al. 2003), and details of the composting process (Miller et al. 2005) have been previously reported.

Manure, compost, and inorganic fertilizer were applied annually to the plots in the fall (October) of 1998 through 2005. Manure was incorporated to a depth of approximately 20 cm using an offset disc cultivator. 'Duke' barley was used in 1999–2004, and 'Kasota' was used in 2005. The crop was seeded in May at a rate of 134 kg ha^{-1} and irrigated with a side-roll system and the amount of irrigation recorded. The crop was harvested in August 2006 at the silage, soft-dough, or Zadock's growth stage 85, at between 60 and 70 % moisture content. The crop was harvested by cutting above-ground plant material (≥10 cm) from 16 m^{2} areas from the middle of each plot with a forage harvester and total fresh weight were measured. Plant sub-samples oven-dried at 60 °C, weighed and were fine-ground (<150 μm) in a Cyclone plant tissue grinder (Udy Corp., Fort Collins, CO, USA) before analyses for total C and N. Total plant C and N were

Table 2 Climatic conditions, irrigation water applied, growing degree days, and seeding date of forage barley on experimental plots at Lethbridge from the time of establishment in fall of 1998 to 2006

Year	Precipitation		Irrig. May–August (mm)	Avg. temp. May–August (°C)	Total evaporation May–August (mm)	Total sunshine May–August (h)	GDD
	April (mm)	May–August (mm)					
1998	–	296	–	–	–	–	–
1999	41.5	229	229	15.0	1,084	NA	1,073
2000	37.4	89	330	16.5	1,235	NA	1,100
2001	44.0	65	279	17.5	1,283	636	1,066
2002	30.7	425	152	15.2	996	1,047	939
2003	68.4	123	178	16.8	1,134	1,050	1,323
2004	18.4	266	191	15.1	879	941	1,015
2005	25.5	375	152	15.4	1,040	1,048	1,091
2006	43.7	140	152	17.5	1,237	1,178	1,016
LTM[a]	31.8	189	–	15.3	1,132	1,133	1,069

GDD growing degree day, *NA* not available

[a] LTM, long-term (30-year) mean for April (second column) or for May to August (columns 3, 5, 7); The exception is for evaporation and GDD, where the LTM is the average from 1999 to 2006

analyzed using the Dumas automated combustion technique (McGill and Fiqueiredo 1993) using a CNS analyzer (Carla Erba, Milan, Italy). Total plant N uptake (PNU) was calculated by multiplying total plant dry weight and plant N concentration.

Amendment analysis

Fresh or composted manure was sampled from piles before land application. Twenty random shovelfuls of material were taken from each pile, composited into one sample, and then between 5 and 36 sub-samples were taken from the composite pile for chemical analyses. All manure samples were oven-dried at 60 °C, ground to pass a 2-mm sieve, and then extracted for chemical analyses. The exception was NO_3-N and NH_4-N, where extractions were conducted on fresh manure samples the day of sampling. The NO_3-N and NH_4-N in the manure were extracted using a 1:20 ratio of 10 g of manure and 200 mL of 2 *M* KCl after shaking at low speed for 1 h. The NH_4-N was determined using the Berthelot reaction on the autoanalyzer (Technicon Industrial Systems, 1978). Electrical conductivity (EC) and pH in manure were determined on 1:5 manure and water extracts (20 g manure and 100 mL distilled water) after shaking at low speed for 1 h. Samples for total C and N analyses were also oven-dried at 60 °C and finely ground to pass a 150-μm sieve. Organic C and N were determined using Dumas automated combustion technique using a CNS analyzer (Carla Erba, Milan, Italy). Details of extraction methods and chemical analysis have been previously reported by Miller et al. (2003). Chemical analysis and cumulative total N applied in eight years of fresh and composted beef cattle manure application are reported by Miller et al. (2009) and summarized in Tables 3 and 4.

Soil sampling and analysis

Composite soil samples were collected from 0- to 15-cm depth of each plot in spring of 2006 before seeding. Soils were air-dried and sieved (<2-mm) before analysis. Soil texture (pipette method following removal of carbonates and organic matter; Gee and Bauder 1986) and soil pH (1:1 soil:water suspension) were determined. Electrical conductivity (EC) of soil samples was determined by measuring the electrical resistance of 1:1 soil water suspension (Table 4). The SOC and SON were measured by the dry combustion method following carbonate removal using a LECO CNS-1000 analyzer (Table 6). A modification of the Stanford and Smith (1972) long-term aerobic incubation procedure was used to measure potentially

Table 3 Chemical analysis of fresh (FM) and composted (CM) manure containing straw or wood-chip bedding (from Miller et al. 2009)

Parameter[a]	FM-straw	CM-straw	FM-wood	CM-wood
Dry matter (g kg^{-1})	598 ± 94[b]	671 ± 97	598 ± 95	721 ± 97
pH	8.3 ± 0.1	8.0 ± 0.1	7.6 ± 0.2	7.5 ± 0.2
EC (dS m^{-1})	9.2 ± 1.1	9.6 ± 0.4	6.7 ± 0.4	5.8 ± 0.3
Total C (g kg^{-1})	239 ± 23.5	191 ± 15.0	340 ± 6.9	269 ± 21.0
Total N (g kg^{-1})	16.4 ± 0.6	16.4 ± 0.7	15.8 ± 0.8	14.3 ± 0.8
C:N ratio	14.6 ± 1.4	11.5 ± 0.5	22.2 ± 1.0	18.4 ± 0.8
NH_4-N (mg kg^{-1})	1,145 ± 240	434 ± 169	947 ± 158	471 ± 193
NO_3-N (mg kg^{-1})	274 ± 82.7	323 ± 93.6	162 ± 27.9	250 ± 45.9

EC electrical conductivity

[a] All chemical analysis expressed on a dry weight basis. Each number is average value over 9 years (1999–2007), and on average 15 samples of each amendment were taken each year (N = 135)

[b] Mean ± 1 SE

mineralizable soil N (N_0) (Curtin and Campbell 2008). Soil samples (30 g) from 0- to 15-cm were mixed with sand (60 g), packed into leaching tubes, and wetted to 55 % of the soils' water-holding capacity by leaching followed by suction (~10 kPa) and incubated at 25 °C for 44 weeks. Therefore, soils' moisture contents were kept at 55 % of the soils' water-holding capacity during the incubation period. The soils were leached periodically (every 2 weeks for the first 12 weeks and every 4 weeks thereafter) with 0.01 *M* $CaCl_2$ followed by a zero-N nutrient solution (Curtin and Campbell 2008). Leachates were analyzed for concentrations of NH_4-N and NO_3-N colorimetrically. The N mineralized in the first 2 weeks period was not used for the curve fitting procedure because this represents the initial flush of mineralization upon rewetting. The following first-order kinetic model was fitted to data using the Marquardt iteration method:

$$N_{min} = N_0[1 - \exp(-kt)] \quad (1)$$

where N_{min} is the net cumulative amount of N mineralized at time, t, N_0 is potentially mineralizable N, and k is the mineralization rate coefficient (Curtin and Campbell 2008). Three different pools of mineralizable N based on long-term aerobic incubation were calculated (Sharifi et al. 2007a):

> [Pool I] The flush in mineral N which occurs in the first 2 weeks period following rewetting. This pool represents a labile mineralizable organic-N pool.
>
> [Pool II] Cumulative amount of N mineralized between weeks 2 and 44 and represents an intermediate pool of mineralizable organic-N.
>
> [Pool III] The amount of SON that was potentially mineralizable, but did not mineralize during the incubation period and was calculated by difference between N_0 predicted from curve fitting and the cumulative amount of N mineralized between weeks 2 and 44 (Pool II). This represents a stable pool of mineralizable organic-N.

The KCl extractable NO_3-N and NH_4-N (KCl–NO_3 and KCl–NH_4) were determined using extraction with 1.7 *M* KCl (20 g air dry soil:100 mL extractent) at room temperature and analyzed colorimetrically using a Technicon TRAACS 800 auto-analyzer (Zebarth and Milburn 2003). Hot KCl extractable NH_4-N (HKCl–NH_4) was determined by heating 9.0 g soil with 60 mL 2 *M* KCl on a digestion block set at 100 °C for 4 h followed by extraction and analysis for NH_4-N as described above (Gianello and Bremner 1986a). The ultraviolet absorbance of the 0.01 *M* $NaHCO_3$ extract at 205 and 260 nm ($NaHCO_3$-205 and $NaHCO_3$-260) was determined as described by Serna and Pomares (1992). Briefly, 2.5 g of soil were shaken in 50 mL of 0.01 *M* $NaHCO_3$ for 15 min in 125 mL Erlenmeyer flasks. The suspension was suction filtered through Whatman no. 42 filter paper and the ultraviolet absorbance of the extract was measured at 205 and 260 nm with an ultraviolet spectrometer (Beckman DU 530 UV/VIS Spectrophotometer, Beckman

Table 4 Soil mineralizable N and field-based indices of soil N supply as affected by eight years of annual application of different solid beef manure and mineral fertilizer N treatments

Treatment[a] ($n = 4$)		pH	EC (dS m^{-1})	Cumulative total N applied[b] (kg ha^{-1})	Soil mineralizable N and field-based indices of soil N supply[c]						
					N_0 (kg N ha^{-1})	k ($week^{-1}$)	Pool I (kg N ha^{-1})	Pool II (kg N ha^{-1})	Pool III (kg N ha^{-1})	TDM[d] (Mg ha^{-1})	PNU[d] (kg N ha^{-1})
FM-S-13	T1	7.7	1.4	1,923	636	0.054	56.7	578	57	5.68	95
FM-S-39	T2	7.9	5.2	5,768	711	0.084	60.8	769	0	5.52	112
FM-S-77	T3	7.9	6.5	11,388	997	0.067	95.4	990	7	4.68	101
FM-W-13	T4	7.9	1.1	1,856	646	0.038	58.8	497	149	5.27	82
FM-W-39	T5	7.7	3.0	5,569	637	0.055	94.6	619	18	5.52	101
FM-W-77	T6	7.8	5.4	10,996	966	0.040	85.6	870	98	4.91	99
CM-S-13	T7	7.7	1.2	1,923	562	0.055	68.9	516	46	5.97	102
CM-S-39	T8	7.6	2.8	5,768	1,068	0.041	106.4	905	164	5.59	106
CM-S-77	T9	7.6	6.2	11,388	1,628	0.052	157.3	1,399	229	5.49	110
CM-W-13	T10	7.6	0.8	1,672	526	0.045	72.3	465	63	5.24	84
CM-W-39	T11	7.6	1.7	5,015	714	0.044	78.4	610	104	5.42	96
CM-W-77	T12	7.5	6.5	9,902	1,555	0.035	121.9	1,215	340	5.22	100
IN	T13	7.7	0.8	900	352	0.094	24.8	347	5	5.09	100
CON	T14	8.0	0.4	0	386	0.036	35.5	294	91	3.95	69

Source of variation	*df*	pH	EC (dS m^{-1})	Cumulative total N applied (kg ha^{-1})	Analysis of variance						
					N_0 kg N ha^{-1}	k ($week^{-1}$)	Pool I (kg N ha^{-1})	Pool II (kg N ha^{-1})	Pool III (kg N ha^{-1})	TDM (Mg ha^{-1})	PNU (kg N ha^{-1})
Decomposition stage [D]	1	NS	***	–	**	*	**	*	**	NS	NS
Bedding [B]	1	NS	NS	–	NS	***	NS	**	NS	NS	**
Rate [R]	2	***	NS	–	***	NS	***	***	NS	*	**
D × B	1	NS	NS	–	NS	NS	NS	NS	NS	NS	NS
D × R	2	NS	NS	–	**	*	NS	**	*	NS	NS
B × R	2	NS	NS	–	NS	NS	NS	NS	NS	NS	NS
D × B × R	2	NS	NS	–	NS	NS	NS	NS	NS	NS	NS
EMS	33	2.11	0.029	–	86,091	0.0002	644	34,670	18,919	0.226	133

Table 4 continued

Source of variation	*df*	pH	EC ($dS\ m^{-1}$)	Cumulative total N applied ($kg\ ha^{-1}$)	Analysis of variance N_0 $kg\ N\ ha^{-1}$	*k* ($week^{-1}$)	Pool I ($kg\ N\ ha^{-1}$)	Pool II ($kg\ N\ ha^{-1}$)	Pool III ($kg\ N\ ha^{-1}$)	TDM ($Mg\ ha^{-1}$)	PNU ($kg\ N\ ha^{-1}$)
CV %		42	2.21	–	33	28	25	23	136	8.8	12

EC electrical conductivity; *EMS* error mean square

*, **, *** significant at 0.05, 0.01 and 0.001 probability levels, respectively; *NS* not significant at 0.05 probability level, *ND* not determined or a negative number

[a] *FM* fresh manure; *CM* composted manure; application rates: 13, 39, and 77 $Mg\ ha^{-1}$ dry weight basis

[b] Cumulative mass of total N applied to experimental plots after eight (2006) annual application of organic or inorganic fertilizer

[c] N_0 = potentially mineralizable N; *k* = mineralization rate coefficient; Pool I = cumulative amount of N mineralized in the first 2 weeks following rewetting; Pool II = cumulative amount of N mineralized between 2 and 44 weeks; Pool III = N_0 minus Pool II; TDM = total barley above = -ground dry-matter yield; PNU = total barley N uptake in above-ground plant

[d] Source of the data for TDM and PNU is Miller et al. (2009)

Coulter, Fullerton, CA, USA). Illinois Soil N Test (ISNT) was determined using the direct diffusion method described by Khan et al. (2001). Phosphate–borate buffer extractable N (PBN) was determined by the method of Gianello and Bremner (1986b). The 4.00 g soil sample, with 40 mL of phosphate–borate buffer (pH 11.2), was direct steam distilled for 8 min to obtain 40 mL of distillate. The NH_4-N was determined in the distillate by back-titration of boric acid with standard 0.01 M H_2SO_4. The NaOH direct-distilled N was measured by steam distillation of a 5 g soil sample with 20 mL of 12.5 M NaOH for 10 min, after which the NH_4-N concentration in the distillate was backtitrated with standard 0.01 *M* H_2SO_4 (Sharifi et al. 2009). The chloroform fumigation extractable C was determined as an index of microbial biomass C (MBC) (Voroney et al. 2007). The POM-C and POM-N were determined by passing a 25 g dispersed air-dried soil sample through a 53 μm sieve (Gregorich and Beare 2008). Retained sand and macroorganic matter were dried and weighed. Carbon and N concentrations were then determined on this retained fraction by dry combustion using a LECO CNS-1000 and the masses of C and N per gram of air-dry soil were calculated as POM-C and POM-N, respectively. All measurement units were converted to units of $kg\ N\ ha^{-1}$ using soil bulk density of each plot measured by the soil core method (Blake and Hartge 1986).

Statistical analysis

Two MIXED model analyses (Littell et al. 1998) were conducted in this study. The first analysis was conducted to determine the effect of the main treatment factors which were manure decomposition stage, bedding material, and manure application rate on the dependent variables. For this analysis, the control and inorganic fertilizer treatments were omitted as there was only one level of each of these factors. Main treatment and interaction effects were tested using least-squares means (LSM). A probability level of $P \leq 0.05$ was considered significant for *F* statistic values and LSM comparisons.

A second MIXED model analysis was conducted to determine the effect of all 14 individual treatments, including the control and inorganic fertilizer treatment, on the dependent variables. The 14 treatments were compared after 8 years (1998–2006) of amendment and fertilizer application. Contrast statement was also used in this analysis to compare the various individual treatments (e.g., control vs. FM) and combinations of treatments (e.g., control vs. FM and CM). A probability level of $P \leq 0.05$ was considered significant for mean and contrast comparisons.

The dry-matter yield (TDM) and PNU in the harvested forage barley were used as field-based indices of SNS (Zebarth et al. 2005). Correlations between laboratory-based and field-based indices of SNS were determined using Spearman's rank correlation (Proc CORR, Spearman) procedure. The significant correlations ($P \leq 0.05$) (positive or negative) were determined to be relevant for further consideration using linear and non-linear regression analyses. Correlation and regression analysis in SAS were conducted using the CORR procedure and REG procedure, respectively. A probability level of $P \leq 0.05$ was considered significant regressions.

Results and discussion

Laboratory-based measures of soil mineralizable nitrogen

The parameter N_0 is a measure of the active soil N fraction (Drinkwater et al. 1996) and was considered as the standard measure of N mineralization potential (Curtin and Campbell 2008). The N_0 represents the sum of mineralizable N Pools II and III (Sharifi et al. 2007a). The N_0 ranged from 352 to 1,628 mg N kg^{-1} soil (Table 4). These values represented an average of 9.3 % of SON, although the N_0/SON ratio was 27 % greater in straw bedding compared with woodchip bedding.

The N_0 was significantly affected by manure decomposition stage, rate of manure application and their interaction. There was no significant effect of bedding on N_0. Greater average N_0 values were observed in CM compared with FM, and N_0 values generally increased with increased manure application rate (Table 4). Values of N_0 were more responsive to manure application rate in CM compared with FM (Fig. 1a). Addition of each Mg ha^{-1} of FM resulted in a 1.3–8.1 kg N ha^{-1} increase in N_0, whereas addition of each Mg ha^{-1} of CM resulted in a 13–18 kg N ha^{-1} increase in N_0. The N_0 values in CON and IN were not significantly different (Tables 4, 5) and were lower than all manured treatments.

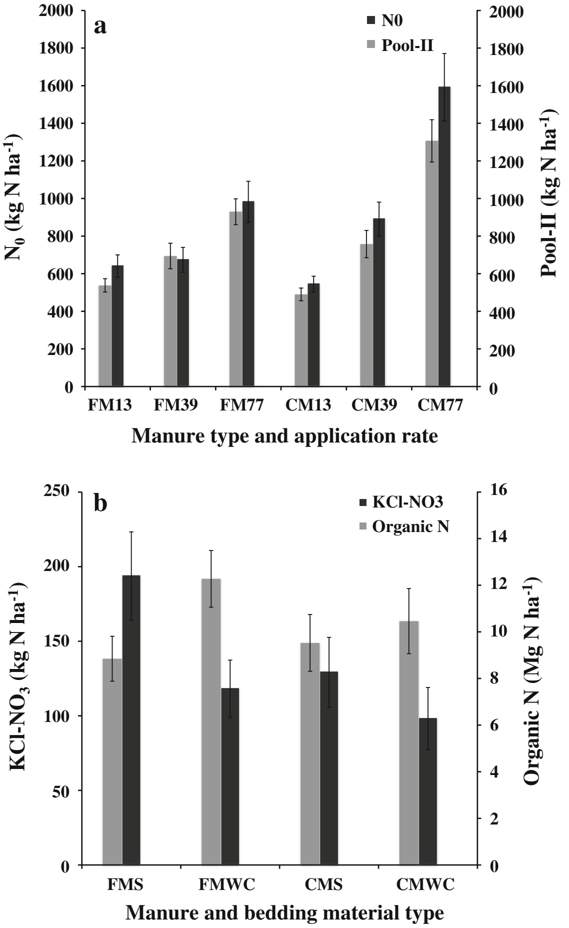

Fig. 1 Effect of manure decomposition stage and application rates on potentially mineralizable N (N_0) and the intermediate mineralizable N pool (Pool II) (**a**), and manure and bedding material type on KCl extractable NO_3-N (KCl–NO_3) and total soil organic N (**b**). *Bars* represent standard errors

The direct comparison of N_0 values calculated in this study against previously published values is difficult due to differences in methodologies used. However, the values we obtained are within the range of values previously reported by Simard and N'Dayegamiye (1993; 232–1,976 kg N ha^{-1}, assuming a soil bulk density of 1.2 Mg $\mathrm{m}^{-3;}$; 55.4 weeks incubation at 20 °C) for 20 meadow soils in Quebec, Canada, but were greater than those reported by Sharifi et al. (Sharifi et al. 2008; 101–284 kg N ha^{-1}) for a long-term beef manure amended potato soil in Maine, USA; by Sharifi et al. (2011; 182–480 kg N ha^{-1}) for a long-term beef manure amended forage grass in Eastern Canada; by Sbih et al. (2003; 158–423 kg N ha^{-1}, assuming a soil bulk density of

Table 5 Contrast for differences among various combination of all 14 treatments for selected parameters

Treatment[a]	N_0[b]	k	Pool I	Pool II	$CaCl_2$–NO_3	$NaHCO_3$-205	TDM	PNU
CON versus CM-straw								
13	NS	NS	NS	NS	*	***	***	***
39	**	NS	***	***	***	***	***	***
77	***	NS	***	***	***	***	***	***
CON versus CM-wood								
13	NS	NS	*	NS	NS	***	***	NS
39	NS	NS	*	*	NS	***	***	***
77	***.	NS	***	***	***	***	***	***
CON versus FM-straw								
13	NS	NS	NS	*	***	***	***	***
39	NS	***	NS	***	***	***	***	***
77	**	*	***	***	***	***	*	***
CON versus FM-wood								
13	NS	NS	NS	NS	NS	***	***	NS
39	NS	NS	***	*	***	***	***	***
77	**	NS	***	***	***	***	***	***
CON versus IN	NS	***	NS	NS	***	***	***	***

NS not significant at 0.05 probability level

[a] FM, fresh manure; CM, composted manure; application rates: 13, 39, and 77 Mg ha^{-1} dry weight basis; CON, control with no manure and no fertilizer; IN, inorganic fertilizer consist of 100 kg N ha^{-1} and 17 kg P ha^{-1}

[b] N_0 = potentially mineralizable N; k = mineralization rate coefficient; Pool I = cumulative amount of N mineralized in the first 2 weeks following rewetting; Pool II = cumulative amount of N mineralized between 2 and 44 weeks; Pool III = N_0 minus Pool II; $NaHCO_3$-205 and -260 = ultraviolet absorbance of 0.01 *M* $NaHCO_3$ extract at 205 and 260 nm, respectively.; TDM = total barley above = -ground dry-matter yield; PNU = total barley N uptake in above-ground plant

1.2 Mg m^{-3}; 56 weeks incubation at 25 °C) for 34 dairy manure amended meadow soils in Quebec, Canada; and by Griffin and Laine (Griffin and Laine 1983; 261–788 kg N ha^{-1}, assuming a soil bulk density of 1.2 Mg m^{-3}; 40 weeks incubation at 35 °C) for 17 soils amended with beef manure, poultry manure and sewage sludge in USA. The greater values of N_0 in this study compared with most of the previous studies could be related to cumulative effect of the long-term annual application of organic amendments at high rates in combination with high inherent SON in the Chernozemic soils in this study. The observed ratio of N_0 to SON was in the range (9–10 %) reported by Sharifi et al. (2008; 2011) for long-term beef manure amended soils in northeastern USA and eastern Canada. As the cumulative amount of added total N in CM and FM was comparable (Table 4), the more rapid increase in N_0 with increase in application rates of CM compared with FM can be attributed to more recalcitrant forms of organic N in CM than in FM.

The k values ranged from 0.035 to 0.094 week^{-1} (Table 4). This range is similar to the range of values reported by Curtin and Wen (1999; 0.025–0.178 week^{-1}), Sharifi et al. (2008; 0.013–0.136 week^{-1}), and Sharifi et al. (2011; 0.023–0.107 week^{-1}). In contrast, Stanford and Smith (1972) found that the value of k was nearly constant across soils at 0.050 ± 0.009 week^{-1}.

There were significant manure decomposition stage × bedding and manure decomposition stage × manure application rate on k values (Table 4). Bedding type had no effect on k at different rates of CM with straw bedding or wood-chip bedding, however, medium and high rates of FM with straw bedding resulted in significantly ($p < 0.1$) higher k values compared with the control. Values of k were 54 % greater for straw compared with wood-chip bedding for FM, whereas for CM, k values were 19 % greater for straw compared with wood-chip bedding. The k values in the IN treatment (0.094 week^{-1}) was numerically greater than for all other treatments, and

Table 6 Mean values for measures of N availability as affected by eight years of annual applications of different beef manure and mineral fertilizer N treatments. Soil samples were collected from 0-15 cm depth in spring of 2006

Treatment[a] (n = 4)		Measures of N availability[b]														
		$CaCl_2$–NO_3 (kg ha^{-1})	$CaCl_2$–NH_4	KCl–NO_3	KCl–NH_4	HKCl-NH_4	$NaHCO_3$-205 (abs units)	$NaHCO_3$-260	ISNT-N (kg N ha^{-1})	NaOH-DD	PBN	MBC (kg C ha^{-1})	POM-C (Mg ha^{-1})	POM-N	SOC	SON
FM-S-13	T1	109	2.63	88.4	6.74	32.4	3.00	0.83	412	733	274	719	15.2	3.34	58.0	5.50
FM-S-39	T2	197	32.4	188	39.3	81.5	3.50	1.61	582	1,010	448	861	56.0	3.91	94.6	8.80
FM-S-77	T3	206	12.3	305	11.4	91.1	3.53	1.60	680	1,191	416	761	80.3	6.51	124	12.2
FM-W-13	T4	55.1	3.20	45.6	6.91	38.1	2.21	0.62	407	740	407	1,590	41.9	2.22	69.6	7.84
FM-W-39	T5	110	10.2	122	15.8	85.7	3.11	0.80	647	1,130	485	1,217	85.5	5.21	139	15.5
FM-W-77	T6	132	14.7	187	16.1	129	3.44	1.44	713	1,340	519	595	103	6.73	182	13.6
CM-S-13	T7	86.0	1.92	49.5	4.61	29.3	2.61	0.70	397	704	328	1,003	24.1	1.70	52.8	5.41
CM-S-39	T8	119	3.01	117	8.23	47.5	3.34	1.21	584	1,026	383	1,723	52.3	4.41	86.8	8.83
CM-S-77	T9	235	9.54	221	22.6	88.6	3.52	1.31	771	1,379	475	970	88.8	7.74	145	14.4
CM-W-13	T10	57.9	1.51	35.8	5.53	32.7	2.03	0.63	566	720	317	760	31.6	1.93	66.9	5.74
CM-W-39	T11	73.9	2.94	77.8	8.42	70.6	3.03	1.04	646	1,074	385	1,567	75.7	4.60	111	9.12
CM-W-77	T12	109	21.6	181	21.3	183	3.50	2.02	1,007	1,669	492	1,340	128	8.11	223	16.6
IN	T13	31.2	0.232	30.6	2.61	12.7	1.31	0.34	271	487	319	681	8.1	0.41	33.1	3.80
CON	T14	103	0.541	119	3.50	16.7	2.44	0.32	275	489	291	432	8.7	0.43	34.0	6.71

Source of variation		Analysis of variance														
		$CaCl_2$–NO_3 (kg ha^{-1})	CaCl2–NH_4	KCl–NO_3	KCl–NH_4	HKCl–NH_4	$NaHCO_3$-205 (abs units)	$NaHCO_3$-260	ISNT-N (kg N ha^{-1})	NaOH-DD	PBN	MBC (kg C ha^{-1})	POM-C (Mg ha^{-1})	POM-N	SOC	SON
Decomposition stage [D]		NS	*	***	NS	NS	NS	NS	**	NS	NS	**	NS	NS	NS	NS
Bedding [B]		***	NS	***	NS	**	***	NS	**	*	*	NS	***	NS	***	***
Rate [R]		***	**	***	*	***	***	***	***	***	***	**	***	***	***	***
D × B	1	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
D × R	2	0.093	*	NS	*	NS	NS	NS	NS	*	NS	**	NS	NS	**	***
B × R	2	NS	*	NS	NS	*	**	NS	NS	NS	NS	NS	NS	NS	**	NS
D × B × R	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	*
EMS	33	1,558	95.4	1,267	166	928	0.055	0.238	12,075	24,189	6,437	113,629	233	0.943	447	3.44
CV %		32	101	26	93	30	7.7	43	18	15	20	31	23	21	19	18

EMS error mean square

*, **, *** Significant at 0.05, 0.01 and 0.001 probability levels, respectively; NS, not significant at 0.05 probability level

[a] FM, fresh manure; CM, composted manure; application rates: 13, 39, and 77 Mg ha^{-1} dry weight basis; CON, control with no manure and no fertilizer; IN, inorganic fertilizer consist of 100 kg N ha^{-1} and 17 kg P ha^{-1}

[b] $CaCl_2$–NO_3 and –NH_4=NO_3-N and NH_4-N leached for the soil incubation columns at t = 0 using 0.01 M $CaCl_2$; KCl–NO_3 = 2 M KCl extractable NO_3-N at 0–15-cm soil depth; KCl–NH_4 = 2 *M* KCl extractable NH_4-N at 0–15-cm soil depth; HKCl–NH_4 = 2 *M* 100 °C KCl extractable NH_4; $NaHCO_3$-205 and -260 = ultraviolet absorbance of 0.01 *M* $NaHCO_3$ extract at 205 and 260 nm, respectively; ISNT-N = Illinois Soil N Test for estimating amino sugar-N; NaOH-DD = direct distillation with NaOH (20 mL 12.5 M); PBN = direct distillation with phosphate-borate buffer (pH 11.2); MBC = microbial biomass carbon by fumigation extraction method; POM-C = particulate organic matter-C; POM-N = particulate organic matter-N; SOC = soil organic carbon; SON = soil organic nitrogen

the k values in the control treatment (0.036 week^{-1}) were numerically lower than almost all other treatments. The lower values of k for wood-chip than for straw bedding likely reflects the greater content of C in the form of lignin in wood-chips (~280 g kg^{-1}) compared with straw (~110 g kg^{-1}) (Larney et al. 2008). Decomposition and N release generally occurred faster for residues with lower C/N ratios and lignin and polyphenol contents (Seneviratne 2000). In a study of green manure crops, leaves decomposed five times faster than stems, decomposition was closely related to cell wall content, and N release was most dependent on the lignin/N ratio (Cobo et al. 2002). Mendham et al. (2004) reported that biochemical characteristics of added organic residues other than the C/N ratio had the main influence on net N mineralization rates.

Pool I ranged from 25 to 157 mg N kg^{-1} soil (Table 4). Pool I was 28 % greater for CM compared with FM, but was not significantly affected by bedding type. Pool I increased linearly with manure application rate with the average increase of 0.80 kg N ha^{-1} per Mg of organic amendment application. The lowest values of Pool I were measured for the CON and IN treatments (Table 4).

Pool II ranged from 294 to 1,399 kg N ha^{-1} (Table 4) and constituted 76–99 % of N_0, while Pool III constituted 1–24 % of N_0, averaged across all treatments. Pool II was 18 % greater for CM compared with FM, and 21 % greater for straw compared with wood-chip bedding. There was a significant manure decomposition stage × rate interaction on Pool II where Pool II increased more rapidly with increasing application rate for CM than for FM (Fig. 1a).

Pool III ranged from 0 to 340 kg N ha^{-1} and had the greatest CV values of any mineralizable N parameter (Table 4). Pool III was three times greater for CM compared with FM, but was not significantly affected by bedding material. There was a significant manure decomposition stage × rate interaction on Pool III, where Pool III increased with increasing rate of CM but was not affected by rate of FM.

Previous studies observed an increase in N_0 as a result of long-term application of an organic amendment (Flavel and Murphy 2006; Griffin 2008), where greater amendment application rates resulted in proportionally greater values of N_0 (Whalen et al. 2001). Mallory and Griffin (2007) reported a 100 % increase in net N mineralization by history of solid beef manure application in a potato–barley rotation using a cumulative measurement of mineral N during a 282 day aerobic incubation. Similarly, Willson et al. (2001) found that N_0 was increased by the addition of dairy manure compost and Sharifi et al. (2011) found that N_0 was increased by long-term application of semi-solid beef manure. Solid beef manure commonly contains organic N compounds with high resistance to mineralization (Beauchamp 1986) and this suggests that annual application of organic amendments may build up the mineralizable N pools coupled with an increased risk of N leakage to the environment (Sharifi et al. 2011). The build up of mineralizable N pools was enhanced in the current study by the composting process.

It is useful to note that the long-term manure applications in this semi-arid environment had a significant effect on soil EC (Table 4). Soil EC increased with increasing application rate, but was not significantly affected by manure decomposition stage or by bedding material.

The increase in EC of the soil as result of higher application rates of FM or CM (Table 4) resulted in lower MBC values (Table 6), which consequently could have impacted N mineralization and nitrification. The soil N mineralizable pools and mineralization rate can also be indirectly influenced by a history of amendment application through effects on other edaphic factors such as soil pH, soil physical properties and soil microbiological communities (Mallory and Griffin 2007).

Laboratory-based measures of nitrogen availability

The KCl-NO_3 ranged from 31 to 305 kg N ha^{-1} (average of 126 kg N ha^{-1}) and KCl-NH_4 ranged from 3 to 39 kg N ha^{-1} (average of 12 kg N ha^{-1}) across all treatments (Table 6). The KCl–NO_3 and KCl–NH_4-N constituted 1.32 and 0.12 % of the average SON, respectively. The SMN ranged from 33 to 344 kg N ha^{-1} (average 139 kg N ha^{-1}) and consisted of 9 % of NH_4-N and 91 % NO_3-N. There was a significant manure decomposition stage × bedding interaction on KCl–NO_3 where values of KCl–NO_3 were greater and more responsive to bedding for FM than for CM. The KCl–NO_3 also increased with increased manure application rate. The KCl–NH_4 content was significantly affected by interaction

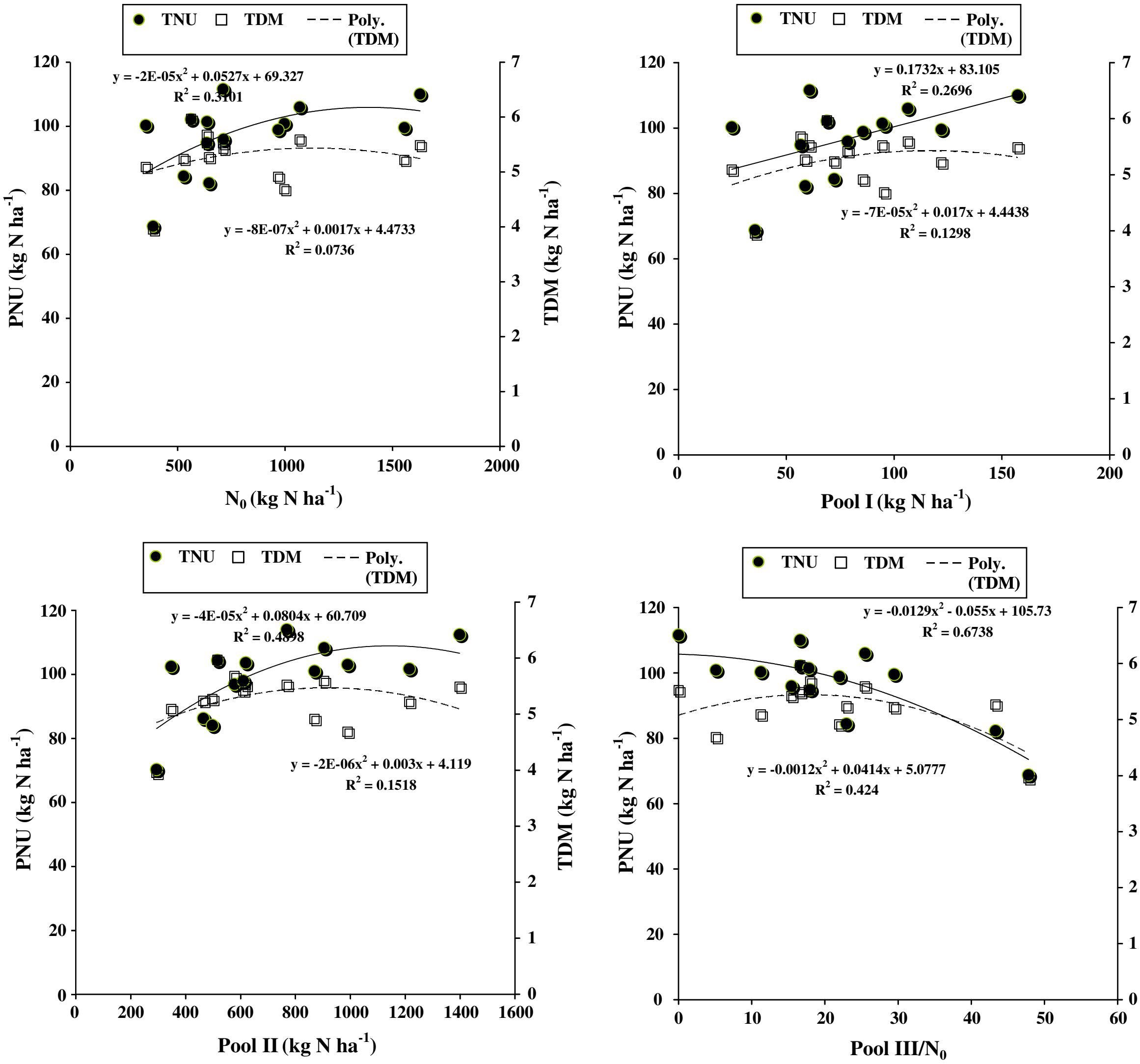

Fig. 2 Relationships between total barley N uptake (PNU) or total barley dry-matter yield (TDM) and potentially mineralizable N (*N_0*), the readily mineralizable N pool (Pool I), the intermediate mineralizable N pool (Pool II) and the stable mineralizable N pool (Pool III) to *N_0* ratio

between manure decomposition stage and application rate. The KCl–NH_4 content responded linearly to increase in CM rates, however this response was quadratic or linear plateau for FM. In most cases values of KCl–NH_4 were small in comparison with KCl–NO_3. The hot KCl–NH_4 was on average 5.4 times greater that of KCl–NH_4, with values ranging from 13 to 183 kg N ha^{-1} (Table 6) and accounted for 0.33–1.1 % of total SON. The hot KCl–NH_4 was significantly greater for wood-chip than for straw bedding, indicating that wood-chips are an effective absorbent of N fraction, which may become available after strong chemical treatment. Increasing manure application rate also increased hot KCl–NH_4 whereas there was no effect of manure decomposition stage on hot KCl–NH_4.

The $CaCl_2$–NO_3 values ranged from 31 to 235 kg N ha^{-1} and were found to be similar to that of KCl–NO_3. The UV absorbance of 0.01 *M* $NaHCO_3$ extracts ranged from 1.31 to 3.53 at 205 nm and from 0.29 to 1.96 at 260 nm (Table 6). These values are slightly greater than the values reported by Hong et al.

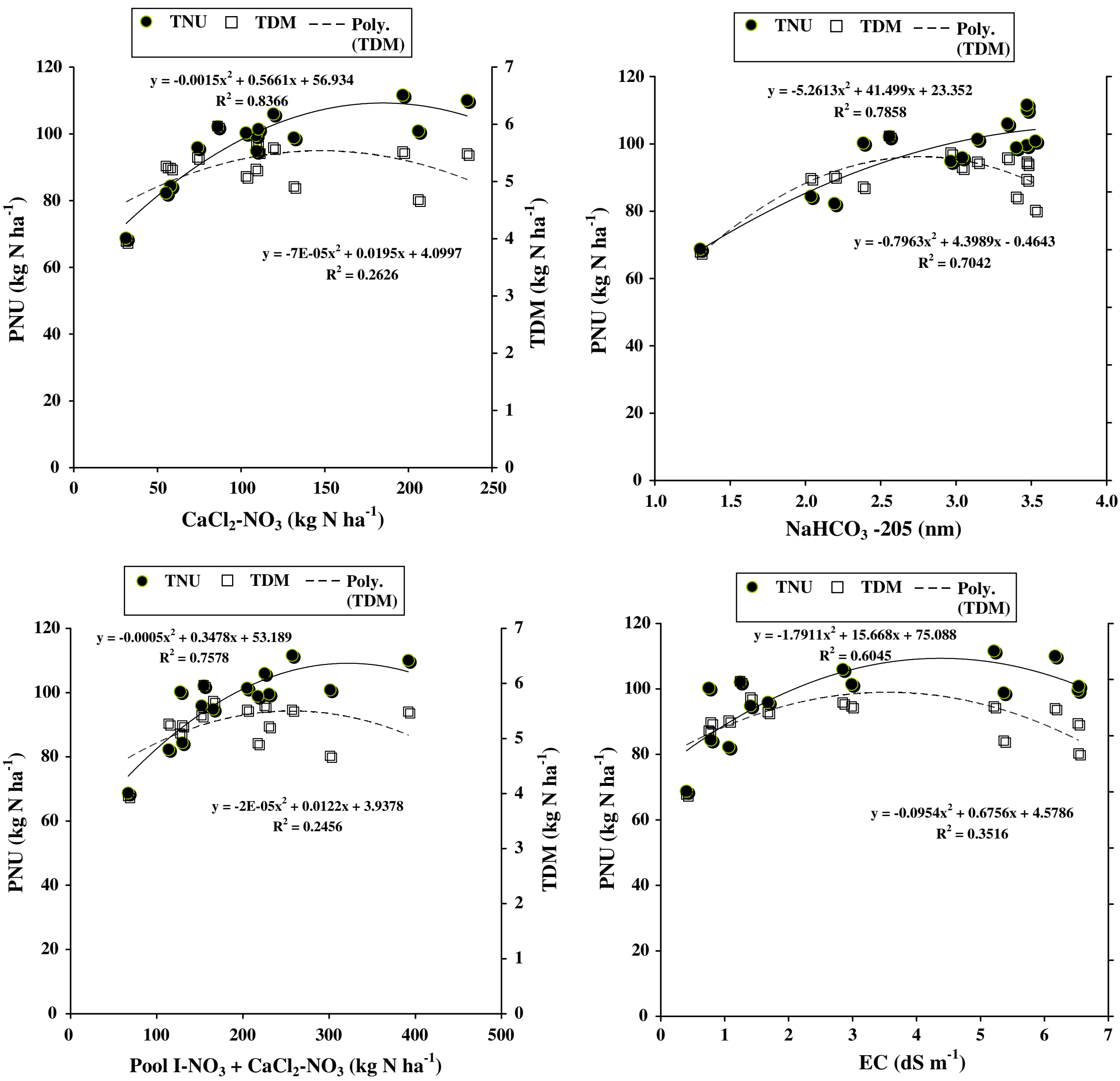

Fig. 3 Relationships between total barley N uptake (PNU) or total barley dry-matter yield (TDM) and $CaCl_2$ extactable NO_3-N ($CaCl_2$–NO_3), the UV absorbance of 0.01 *M* $NaHCO_3$ extracts at 205 nm, the readily mineralizable N pool (Pool I) plus $CaCl_2$–NO_3, and soil electrical conductivity (EC)

(1990; 0.58–2.49 at 205 nm and 0.20–0.44 at 260 nm), by Serna and Pomares (1992; 0.51–2.17 at 205 and 0.24–0.86 at 260 nm), and by Sharifi et al. (2011; 0.71–2.58 at 205 nm and 0.38–1.35 at 260 nm). The $NaHCO_3$-205 was greater for straw than for wood-chip bedding and increased with manure application rate, but was not affected by manure decomposition stage. In comparison, $NaHCO_3$-260 increased with manure application rate, but was not affected by manure decomposition stage or bedding.

Values of ISNT-N were significantly greater for CM than FM, greater for wood-chip than for straw bedding, and increased with manure application rate (Table 6). In comparison, the NaOH-DD was greater for wood-chip than straw bedding, but was not affected by manure decomposition stage. There was a manure decomposition stage × rate interaction on NaOH-DD where values of NaOH-DD increased more rapidly with increasing application rate for CM than for FM. In contrast, there was a significant response of PBN to manure application rate only.

The MBC ranged from 432 to 1,723 kg C ha^{-1} with an average value of 1,016 kg C ha^{-1} (Table 6) and accounted for 0.4–2.3 % of total SOC. This is within the range of values reported by Sharifi et al. (2011; 333–2,010 kg C ha^{-1}) for a soil under forage grass with long term history of beef manure application. There was a significant manure decomposition stage × rate × bedding interaction on MBC. Maximum values of MBC occurred at rates 13 or 39 Mg ha^{-1} depending on manure decomposition stage and bedding, and were generally lower for FM with straw bedding than for other treatment combinations.

The POMC ranged from 8 to 128 Mg ha^{-1}, and was equivalent to 24–68 % of total SOC (Table 6). Similarly, the POMN ranged from 0.4 to 8.1 Mg ha^{-1}, and was equivalent to 7–55 % of total SON. The POMN was the largest of the organic N fractions evaluated. The C:N ratio of POM was wider (average 16, range 11–21) than that of the whole soils (average 10, range 6–13), reflecting the dominant influence of C through bedding (straw or woodchip) on this pool (Christensen 1992). The POMC was greater for woodchip than for straw bedding and increased with manure application, but was not affected by manure decomposition stage.

Relationships between field-based indices and laboratory-based measures of nitrogen supply

The field based indices of SNS (i.e., TDM and PNU) are reported and discussed by Miller et al. (2009). Correlation coefficients were calculated between laboratory-based measures of soil N availability and TDM or PNU as field-based indices of N supply. Among laboratory-based measures of soil N supply, $CaCl_2$–NO_3 (r = 0.78), $NaHCO_3$-205 (r = 0.86), a combination of Pool I-NO_3 and $CaCl_2$-NO_3 (r = 0.76), Pool III:N_0 ratio (r = −0.79) and EC (r = 0.61) were strongly associated with PNU, and $NaHCO_3$-205 (r = 0.44), EC (r = 0.35) and $CaCl_2$–NO_3 (r = 0.19) were associated with TDM. Linear correlation coefficients of measures of N availability with TDM were low due to lack of a linear relationship. The N_0, Pool I and Pool II were weakly correlated with PNU (r = 0.50, 0.52, and 0.62, respectively). There was no strong correlation between ISNT, MBC, NaOH-DD, POMC, POMN, SOC, SON and Hot KCl–NH_4 either with PNU or TDM. Plots of PNU and TDM against the most successful laboratory-based measures of N availability were used to identify the suitability of using these parameters for prediction of N supply in the field (Figs. 2, 3). The $CaCl_2$–NO_3 and $NaHCO_3$ were good predictors of PNU and predicted 84 and 79 % of the variability in this parameter, respectively. Multi-variable regression and stepwise approaches were tested but no improvement in the relationships was achieved. The superiority of mineral N based indicator to N mineralization based indicators in predicting PNU and TDM can be attributed to large quantity of soil mineral N in soil before planting. A portion of this mineral N is as a result of carryover from previous growing season. Therefore, a great proportion of SNS in this soil was comprised of soil mineral N.

Similar to our findings, in a non-amended field potato experiments in New Brunswick and PEI, Canada and Maine, USA, Sharifi et al. (2007b) reported that pre-plant mineral N at 0–30 cm soil depth and $NaHCO_3$-205 were the best predictors of field-based indices of SNS.

Conclusions

Eight years history of amendment application increased soil mineralizable N pools, where greater rates resulted in greater soil mineralizable N. Manure decomposition stage (FM < CM) and application rates (L < M < H) were the dominant factors affecting quantity of active soil organic N fraction. Application of FM and use of straw bedding resulted in a greater quantity of readily available and intermediate mineralizable N, and also increased the rate of N turnover as indicated by greater values of *k*, compared with CM and wood-chip bedding. Composted manure contributed more to the intermediate and stable mineralizable N pools and consequently was more effective in accumulating organic N in soil. The bedding type significantly impacted only *k* and Pool II among potentially mineralizable N parameters. Straw bedding resulted in 17 % greater values for Pool II compared with wood-chip bedding. There was an interaction between decomposition stage and bedding type or rate of application on *k,* where only medium and high rates of FM with straw bedding resulted in higher *k* values compared with control. Greater *k* values were measured in the inorganic fertilizer than in the control treatment.

The relationship between mineralizable N indices and barley TDM or PNU was polynomial. Increased soil mineralizable N in medium and high application rates

(39 and 77 Mg ha^{-1} dry matter basis) did not translate into greater barley yield or N uptake due to abundant soil N supply and high soil EC (close to crop tolerance threshold). Barley yield and N uptake were similar in fresh manure and composted manure with straw or woodchip bedding. High soil EC also resulted in reduced MBC. Among tested laboratory-based measures of N availability, $CaCl_2$–NO_3, and $NaHCO_3$ were the superior predictors of PNU and predicted 84 and 79 % of the variability in this parameter, respectively. Composted beef manure and wood-chip bedding can be recommended as alternatives to FM and straw bedding for barley production is Southern Alberta. Low rate of annual application would be appropriate due to inherent high SNS in Dark Brown Chernozemic soils of this region. Application of fresh or composted manure in semiarid region need to be tailored to crop N and P demand with close monitoring of soil EC.

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References

Alberta Agriculture and Rural Development (1995) Alberta fertilizer guide.Agdex 541-1. AARD, Edmonton

Beauchamp EG (1986) Availability of nitrogen from three manures to corn in the field. Can J Soil Sci 66:713–720

Blake GR, Hartge KH (1986) Bulk Density. In Klute A (ed) Methods of soil analysis. Part 1—physical and mineralogical methods, 2nd edn. American Society of Agronomy, Madison

Carter MR, MacLeod JA (1987) Biological properties of some Prince Edward Island soils: relationship between microbial biomass nitrogen and mineralizable nitrogen. Can J Soil Sci 67:333–340

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

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

Chang C, Cho CM, Janzen HH (1998) Nitrous oxide emission from long-term manured soils. Soil Sci Soc Am J 62:677–682

Christensen BT (1992) Physical fractionation of soil and organic matter in primary particle size and density separates. Adv Agron 20:1–90

Cobo JG, Barrios E, Kass DCL, Thomas RJ (2002) Decomposition and nutrient release by green manures in a tropical hillside agroecosystem. Plant Soil 240:331–342

Curtin D, Campbell CA (2008) Mineralizable nitrogen. In: Carter MR, Gregorich EG (eds) Soil sampling and methods of analysis, 2nd edn. CRC Press, Boca Raton, pp 599–606

Curtin D, Wen G (1999) Organic matter fractions contributing to soil nitrogen mineralization potential. Soil Sci Soc Am J 63:410–415

Drinkwater LE, Cambardella CA, Reeder J, Rice CW (1996) Potentially mineralizable nitrogen as an indicator of biologically active soil nitrogen. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality. Soil Science Society of America, Madison, pp 217–229

Eghball B, Wienhold BJ, Gilley JE, Eigenberg RA (2002) Mineralization of manure nutrients. J Soil Water Conserv 57:470–473

Flavel TC, Murphy DV (2006) Carbon and nitrogen mineralization rates after application of organic amendments to soil. J Environ Qual 53:183–193

Freeze BS, Heigh JT, Larney FJ, Olson AF (1999) Economics of windrow composting and land application of manure. Proc. Manure Management'99. Saskatoon, SK, pp 311–320

Gee GW, Bauder JW (1986) Particle-size analysis. In Klute A (ed) Methods of soil analysis. Part 1, 2nd edn. Agron. Monogr. 9. ASA and SSSA, Madison, pp 383–411

Gianello C, Bremner JM (1986a) A simple chemical method of assessing potentially available organic nitrogen in soil. Commun Soil Sci Plant Anal 17:195–214

Gianello C, Bremner JM (1986b) Comparison of chemical methods of assessing potentially mineralizable organic nitrogen in soil. Commun Soil Sci Plant Anal 17:215–236

Gregorich EG, Beare MH (2008) Physically uncomplexed organic matter. In: Carter MR, Gregorich EG (eds) Soil sampling and methods of analysis, 2nd edn. CRC Press, Boca Raton, pp 607–616

Griffin TS (2008) Nitrogen availability. In Schepers J, Raun WR (eds) Nitrogen in agricultural systems. Agron Monogr 49. ASA, CSSA, and SSSA, Madison, pp 613–646

Griffin GF, Laine AF (1983) Nitrogen mineralization in soils previously amended with organic wastes. Agron J 75:124–129

Haney RL, Hons FM, Sanderson MA, Franzluebbers AJ (2001) A rapid procedure for estimating nitrogen mineralization in manured soil. Biol Fertil Soils 33:100–104

Hao X, Chang C (2003) Does long-term heavy cattle manure application increase salinity of a clay loam soil in semi-arid southern Alberta? Agric Ecosyst Environ 94:89–103

Hassink J (1995) Prediction of the non-fertilizer N-supply of mineral grassland soils. Plant Soil 176:71–79

Helgason BL, Larney FJ, Janzen HH, Olson BM (2007) Nitrogen dynamics in soil amended with composted cattle manure. Can J Soil Sci 87:43–50

Hong SD, Fox RH, Piekielek WP (1990) Field evaluation of several chemical indexes of soil nitrogen availability. Plant Soil 123:83–88

Khan SA, Mulvaney RL, Hoet RG (2001) A simple soil test for detecting sites that are nonresponsive to nitrogen fertilization. Soil Sci Soc Am J 65:1751–1760

Larney FJ, Blackshaw RE (2003) Weed seed viability in composted beef cattle feedlot manure. J Environ Qual 32:1105–1113

Larney FJ, Yanke LJ, Miller JJ, McAllister TA (2003) Fate of coliform bacteria in composted beef cattle feedlot manure. J Environ Qual 32:1508–1515

Larney FJ, Buckley KE, Hao X, McCaughey WP (2006) Fresh, stockpiled and composted beef cattle feedlot manure: nutrient levels and mass balance estimates in Alberta and Manitoba. J Environ Qual 35:1844–1854

Larney FJ, Olson AF, Miller JJ, DeMaere PR, Zvomuya F, McAllister TA (2008) Physical and chemical changes during composting of wood chip-bedded and straw- bedded beef cattle feedlot manure. J Environ Qual 37:725–735

Littell RC, Henry PR, Ammerman CB (1998) Statistical analysis of repeated measures data using SAS procedures. J Anim Sci 76:1216–1231

Mallory EB, Griffin TS (2007) Impacts of soil amendment history on nitrogen availability from manure and fertilizer. Soil Sci Soc Am J 71:964–973

McGill WB, Fiqueiredo CT (1993) Total nitrogen. In: Carter MR (ed) Soil sampling and methods of analysis. Lewis Publ, Boca Raton, pp 201–211

Mendham D, Heagney E, Corbeels M, O'Connell A, Grove T, McMurtrie R (2004) Soil particulate organic matter effects on nitrogen availability after afforestation with *Eucalyptus globulus*. Soil Biol Biochem 36:1067–1074

Miller JJ, Beasley BW, Yanke LJ, Larney FJ, McAllister TA, Olson BM, Selinger LB, Chanasyk DS, Hasselback P (2003) Bedding and seasonal effects on chemical and bacterial properties of feedlot cattle manure. J Environ Qual 32:1887–1894

Miller JJ, Beasley BW, Larney FJ, Olson BM (2005) Soil salinity and sodicity after application of fresh and composted manure with straw or wood-chips. Can J Soil Sci 85:427–438

Miller JJ, Beasley BW, Drury CF, Zebarth BJ (2009) Barley dry matter yield and nutrient uptake for soil amended with fresh and composted cattle manure. Agron J 101:1047–1059

Rynk R (1992) Editor, On-farm composting handbook. Publ. NRAES-54. Northeast Regional Agricultural Engineering Service, Ithaca

Sbih M, N'Dayegamiye A, Karam A (2003) Evaluation of carbon and nitrogen mineralization rates in meadow soils from dairy farms under transit to biological cropping systems. Can J Soil Sci 83:25–33

Seneviratne G (2000) Litter quality and nitrogen release in tropical agriculture: a synthesis. Biol Fertil Soils 31:60–64

Serna MD, Pomares F (1992) Evaluation of chemical indices of soil organic nitrogen availability in calcareous soils. Soil Sci Soc Am J 56:1486–1491

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Cooper JM (2007a) Evaluation of some indices of potentially mineralizable nitrogen in soil. Soil Sci Soc Am J 71:1233–1239

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Porter GA, Cooper GM, Leclerc Y, Moreau G, Arsenault WJ (2007b) Evaluation of laboratory based measures of soil mineral nitrogen and potentially mineralizable nitrogen as predictors of field-based estimates of soil nitrogen supply in potato production. Plant Soil 301:203–214

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Porter GA (2008) Organic amendment history and crop rotation effects on soil nitrogen mineralization potential and soil nitrogen supply in a potato cropping system. Agron J 100:1562–1572

Sharifi M, Zebarth BJ, Burton DL, Grant CA, Hajabbasi MA, AbbassiKalo G (2009) Sodium hydroxide direct distillation: a method for estimating total nitrogen in soil. Commun Soil Sci Plant Anal 40:2505–2520

Sharifi M, Zebarth BJ, Burton DL, Rodd V, Grant CA (2011) Long-term effects of semi-solid beef manure application to forage grass on soil mineralizable nitrogen. Soil Sci Soc Am J 75:649–658

Simard RR, N'Dayegamiye A (1993) Nitrogen mineralization potential of meadow soils. Can J Soil Sci 73:27–38

Snapp SS, Fortuna AM (2003) Predicting nitrogen availability in irrigated potato systems. HortTechnology 13:598–604

St Luce M, Whalen JK, Ziadi N, Zebarth BJ (2011) Nitrogen dynamics and indices to predict soil nitrogen supply in humid temperate soils. Adv Agron 112:55–102

Stanford G, Smith SJ (1972) Nitrogen mineralization potentials of soils. Soil Sci Soc Am J 36:465–472

Van Herk FH, Cockwill CL, Gusselle N, Larney FJ, Olson ME, McAllister TA (2004) Elimination of *Giardia cysts* and *Cryptosporidium oocysts* in beef feedlot manure compost. Compost Sci Util 12:235–241

Voroney RP, Brookes PC, Beyaert RP (2007) Soil microbial biomass C, N, P, and S. In: Carter MR, Gregorich EG (eds) Soil sampling and methods of analysis, 2nd edn. CRC Press, Boca Raton, pp 637–651

Wen G, Schoenau JJ, Mooleki SP, Inanaga S, Yamamoto T, Hamamura K, Inoue M, An P (2003) Effectiveness of an elemental sulfur fertilizer in an oilseed-cereal-legume rotation on the Canadian Prairies. J Plant Nutr Soil Sci 166:54–60

Whalen JK, Chang C, Olson BM (2001) Nitrogen and phosphorus mineralization potentials of soils receiving repeated annual cattle manure applications. Biol Fertil Soils 34:334–341

Williams JD, Crozier CR, White JG, Sripada RP, Crouse DA (2007) Comparison of soil nitrogen tests for corn fertilizer recommendations in the humid southeastern USA. Soil Sci Soc Am J 71:171–180

Willson TC, Paul EA, Harwood RR (2001) Biologically active soil organic matter fractions in sustainable cropping systems. Appl Soil Ecol 16:63–76

Zebarth BJ, Milburn PH (2003) Spatial and temporal distribution of soil inorganic nitrogen concentration in potato hills. Can J Soil Sci 83:183–195

Zebarth BJ, Leclerc Y, Moreau G, Sanderson JB, Arsenault WJ, Botha E, Wang Pruski G (2005) Estimation of soil nitrogen supply in potato fields using a plant bioassay approach. Can J Soil Sci 85:377–386