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Management of Manure Nitrogen Using Cover Crops

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ABSTRACT

The experiment was conducted to determine whether cover crops reduce N losses of fall-applied liquid hog manure and whether sequestered N by cover crops is "transferred" to subsequent corn (*Zea mays* L.). Two locations (Elora and St. Mary's) in southern Ontario from 2003–2004 were used consisting of six cover crop treatments (red clover [RC] [*Trifolium pratense* L.] fall-killed, RC spring-killed, oat [*Avena sativus* L.] fall-killed, oilseed radish [*Raphanus sativus* L.] fall-killed, perennial ryegrass [*Lolium perenne* L.] spring-killed, and no-cover crop), and three target manure rates (0, 100, and 200 kg N ha^{-1}). Non-legume cover crops positively responded to fall manure application, where biomass increased by 50 to 130%. Red clover biomass increased 0 to 25% at higher manure rate application. A similar trend was found with plant N uptake. Generally applied manure N recovery was low (0–25%) in all the cover crops. Ammonia losses from manure applications to RC was higher than other cover crops due to inability to incorporate manure. During the period corresponding with corn N uptake, non-legume cover crop impact on soil mineral N did not differ from the no cover control. When non-legumes were used as cover crops following manure application, corn biomass, grain yield, and N uptake were equivalent to no cover crop treatment. However, when RC was used as a cover crop, above corn parameters were equivalent for all manure application rates and greater than the no-cover crop treatment, so "transfer" of manure N could not be confirmed.

Use of livestock manure as a source of N for corn is a common practice used worldwide (Schmitt et al., 1995; Loria et al., 2007; Woli et al., 2013). However, time of manure application to soil is critical since manure N can be rapidly lost from the soil system through ammonia (NH_3) volatilization (Amon et al., 2006), nitrate leaching (Long and Sun, 2012), and surface runoff (Smith et al., 2001), thus creating economic losses as well as negative environmental impacts (Maguire et al., 2011). As a result of limitations in manure storage capacity, many livestock producers in Canada apply manure in the fall of the year preceding corn planting. In Ontario, Canada, precipitation typically exceed evapotranspiration in the fall and winter months (Fallow et al., 2003), causing a net downward movement of water in the soil profile creating a situation for potential nitrate leaching. On the other hand, with increasing fertilizer costs, producers must modify their cropping systems to find ways to reduce the dependency on supplemental fertilizers, while at the same time reducing nutrient losses to the environment.

Cover crops have been suggested as a potential solution to address these concerns with the N losses. Cover crops influence N cycling by immobilizing N through plant uptake (Blankenau et al., 2000), and subsequently mineralizing N during the following growing season (Snapp et al., 2005). Immobilization of N by cover crops directly reduces the soil mineral N, thus minimizing nitrate leaching during the periods of high levels of downward movement of soil moisture (Salmerón et al., 2010). The magnitude of the influence by cover crops is determined by biomass production achieved by the cover crop (Martens et al., 2001), method and time of cover crop control (Odhiambo and Bomke, 2001), cover crop species (Parr et al., 2014), and C/N ratio of the cover crop (Quemada and Cabrera, 1995). Further, synchrony between crop N demand and cover crop N release is critical in this process (Crews and Peoples, 2005).

Cover crops ranging from legumes to non-legumes are used in different cropping systems. Cover crops that have been commonly used as winter and spring cover crops are oat (Johnson et al., 1998), rye (De Bruin et al., 2005), oilseed radish (Vyn et al., 2000), perennial ryegrass (Chen et al., 2006), hairy vetch (*Vicia villosa* Roth) (Rosecrance et al., 2000), RC (Jokela et al., 2009), alfalfa (Chen et al., 2006), and buckwheat (*Fagopyrum esculentum* Moench) (Bicksler and Masiunas, 2009). Among the different livestock manures used as nutrient sources for crop production, application of hog manure as a N source for corn production is a common

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Abbreviations: ANE, apparent nitrogen equivalent; FNE, fertilizer nitrogen equivalent; RC, red clover.

practice (Woli et al., 2013). Cover crops can be used to enhance the retention of applied manure N and minimize N losses (Cambardella et al., 2010). We conducted a study to evaluate the possibility of using different cover crops to immobilize the N from hog manure which was applied in late summer and supposed to release the immobilized N to the following corn crop.

Specific objectives of the study were (i) to determine the effect of cover crop treatments on cover crop N uptake, ammonia losses, and soil mineral N levels following fall-applied manure applications, and (ii) to determine the effect of cover crop treatments following fall-applied manure application on N availability and uptake by corn the following year.

MATERIALS AND METHODS

Site Description and Experimental Design

A field experiment was conducted over the 2003–2004 growing seasons at two different locations in southern Ontario; Elora (Elora research station, 43°39′ N, 80°25′ W, 376 m above mean sea level), and St. Mary's (commercial farm, 43°16′ N, 81°04′ W, 369 m above mean sea level). Soil characteristics, site descriptions, manure data are presented in Table 1, and weather data presented in Fig. 1.

The six cover crop treatments consisted of (i) RC fall-killed, (ii) RC spring-killed, (iii) perennial ryegrass spring-killed, (iv) oat fall-killed, (v) oilseed radish fall-killed, and (vi) no-cover crop. Each received three liquid hog manure treatments applied at target application rates of 0 (no-manure), 100 (low-manure), and 200 (high-manure) kg N ha^{-1} in the fall of 2003. Red clover was under seeded into growing barley and winter wheat at Elora and St. Mary's, respectively. All the other cover crops were established following barley and winter wheat in Elora and St. Mary's, respectively. The experimental design was randomized complete block design with four replicates where each experimental unit was 6 by 10 m size. In spring 2004, all the experimental units were split into two N fertility treatments of 0 and 200 kg N fertilizer ha^{-1}. This 200 kg N fertilizer application was intended to determine a non-limiting N rate for the assessment of non-N rotation effects from the cover crops.

Table 1. Soil characters, crop heat units, and drainage type at Elora and St. Mary's and liquid hog manure composition applied at Elora and St. Mary's in fall of 2003.

Parameters	Elora	St. Mary's
Soil type	London loam	Huron clay
Organic matter, %	3.0	3.7
Crop heat units	2658	2850
Drainage type	tile drainage	tile drainage
First frost day in 2003†	8 November	8 November
Manure composition		
Dry matter, %	1.6	1.0
Nitrogen, %	0.31	0.21
Phosphorus, %	0.06	0.04
Potassium, %	0.16	0.10
Total salts, mmho cm^{-1}	19.6	13.5
NH_4–N, mg kg^{-1}	2844	1372

† Temperature was below –4°C for more than 6 h.

Manure Application, Cover Crop Establishment, and Incorporation into the Soil

Liquid hog manure was sourced from two commercial farms near Elora and St. Mary's. Bulk tanks were sampled 3 to 5 d before application date and analyzed for total and ammonium N. Analysis results were used to estimate the volume of manure required for each manure N application rate. On the date of application, manure tanks were agitated. Manure was applied manually on 28 Aug. and 3 Sept. 2003 in Elora and St. Mary's, respectively. At time of application, manure was again sampled and analyzed for total and ammonium N. Actual manure N application rates were 0, 134, and 266 kg N ha^{-1} at Elora an d 0, 64, and 128 kg N ha^{-1} at St. Mary's. Manure was incorporated into the soil in all the cover crop treatments, except RC, within 15 min of application to a depth of 7 to 10 cm using a C-tine swept tooth cultivator with harrows at Elora, and a tandem disc at St. Mary's. For the RC treatments, manure was broadcast on top of the clover canopy.

Red clover seeds (variety RAM, seed rate of 35 kg ha^{-1}) were hand broadcasted 3 to 4 mo before manure application, on 22 May 2003 at Elora and on 7 May 2003 at St. Mary's. Perennial ryegrass (variety Common no. 1, seed rate 70 seeds m^{-2}), oat (variety Common no. 1 untreated, seed rate 70 seeds m^{-2}) and oilseed radish (variety Colonial, seed rate 20 kg ha^{-1}) were seeded in 17.5 cm rows using a Tye no-till planter (Tye Company, Lockney, TX), immediately after the manure incorporation. Weeds were controlled in no-cover crop plots using glyphosate [N-(phosphonomethyl) glycine] (rate 1.8 kg ha^{-1}). Under the RC fall-killed treatment, RC plants were killed by applying glyphosate (rate 1.8 kg ha^{-1}) on 20 and 21 Nov. 2003 at Elora and St. Mary's, respectively. Oat and oilseed radish were killed by fall frost events on 8 November at Elora and St. Mary's (Table 1). Spring-killed RC and perennial ryegrass were killed in the spring using a moldboard plow.

Biomass Estimates and Analysis of Cover Crops

Cover crops were sampled for biomass estimates on 10 Nov. 2003 (fall-killed) and 28 Apr. 2004 (spring-killed) in Elora, and 12 Nov. 2003 (fall-killed) and 4 May 2004 (spring-killed) in St. Mary's. Aboveground plant samples were collected from 0.5 m^2 quadrates per plot and oven dried at 80°C for 3 d to determine the dry weight (wt). Dry samples were ground using a Wiley mill and passed through a 1 mm mesh. Total N content of the plant samples were analyzed using LECO FP 428 analyzer.

Establishment of Corn following Cover Crops

Potassium and P fertilizer (0–20–20) were applied before the primary and secondary tillage, at a rate of 416 kg ha^{-1} based on soil nutrient test. All plots were plowed 1 d before planting. In addition to the six cover crop treatments, six N fertilizer treatments (0, 50, 100, 150, 200, and 250 kg N ha^{-1}) were used separately with the no cover crop treatment to evaluate the agronomic value of the manure N with the cover crops and fertilizer treatments. Ammonium nitrate (34–0–0) was used as the N fertilizer and broadcasted at the time of corn planting accordingly. Corn (variety Pioneer 39D82) was planted on 17 and 28 May 2004 at Elora and St. Mary's, respectively using a conventional 76-cm row spaced Max Emerge John Deere

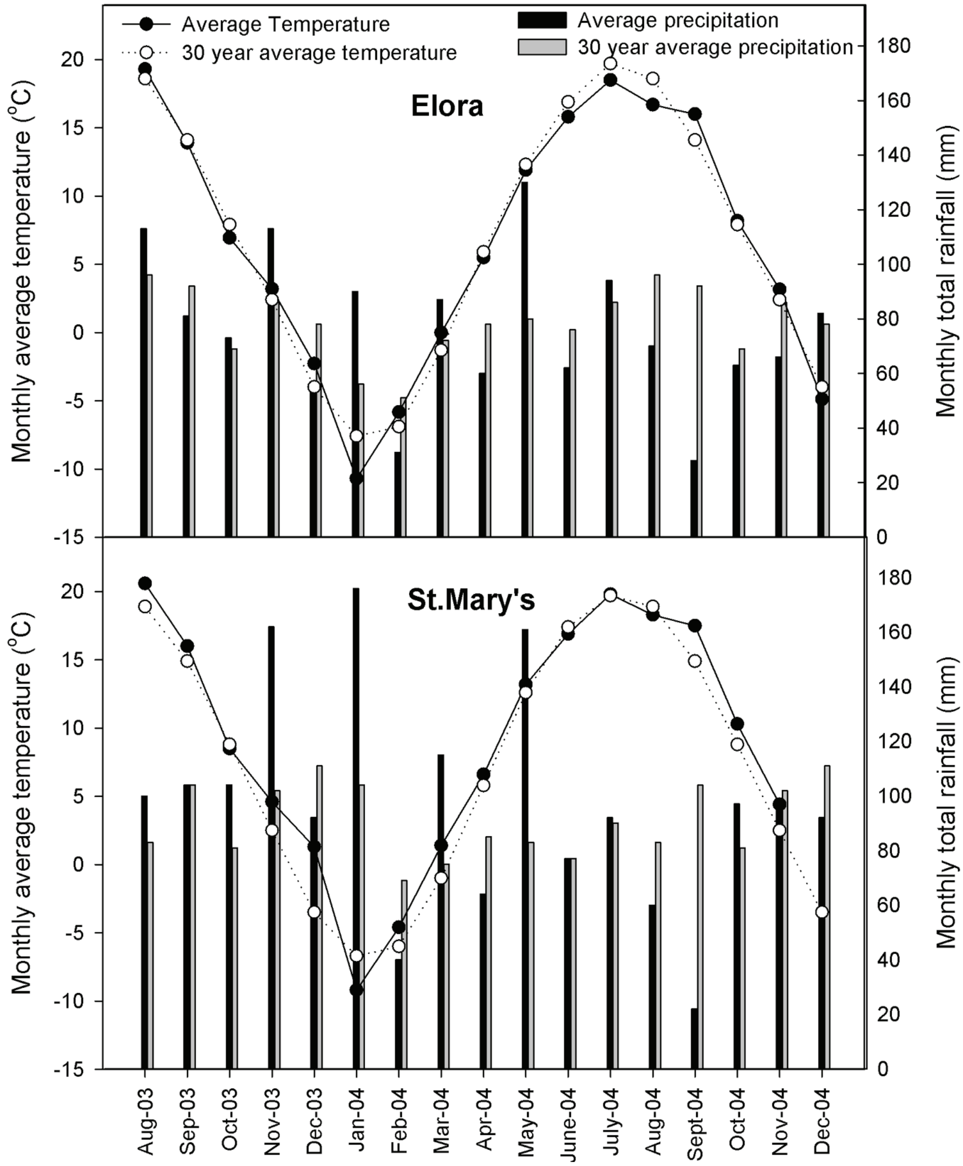

Fig. 1. Average monthly temperature, 30-yr average monthly temperature, average monthly precipitation, and 30-yr average monthly precipitation at Elora and St. Mary's during the experimental period (August 2003–December 2004).

planter with a target population of 75,000 plants ha^{-1}. Weeds were controlled by applying pre-emergence herbicides.

Harvesting and Analysis of Corn

Corn biomass samples were collected three times over the 2004 growing season; (i) 6–8 leaf stage (24 and 29 June), (ii) silking stage (9 and 17 August), and (iii) at harvest (28 October and 12 November) at Elora and St. Mary's, respectively. Corn growth stages were counted using the leaf over method (OMAFRA, 2002). Fifteen and 10 plants were harvested at 6–8 leaf age and silking stage respectively, and dried at 80°C for 3 d to determine dry wt. The aboveground biomass at harvest (without the grain or cob) was determined by harvesting two 5-m rows. Harvested plants were shredded in a leaf shredder in the field and subsamples were dried at 80°C for 3 d to determine dry wt. Dried plant samples were ground using a Wiley Mill, to pass through a 1-mm sieve. Total N content of the ground plant samples was determined using the combustion method on a LECO FP 428 analyzer.

Corn grain yield was determined by harvesting two 5-m central rows from each plot at maturity. Cobs were harvested on 25 Oct. and 9 Nov. 2004 at Elora and St. Mary's, respectively. A subsample of 10 cobs from each plot was dried at 80°C for 3 d to determine dry wt. of cobs and grains. The grain yield was expressed at 15.5% moisture (Beare et al., 2002). The grain N content was determined using a Dickey John Omeg AnalyzerG whole grain analyzer.

Fertilizer nitrogen equivalent (FNE) was determined using the five N fertilizer rates to develop a N response curve specific to each field site. The specific yields from the various rates of manure N and cover crop treatments were then used to back calculate the FNE which would have given the same yield of the specific manure and cover crop treatment (Eq. [1]).

$$\text{FNE} = \frac{-b \pm \sqrt{b^2 - 4c\left(a\text{ - yield}\right)}}{2c} \quad [1]$$

where a = intercept, b = linear coefficient, c = quadratic coefficient, yield = corn yield of N fertilizer treatments.

The equation utilizes the coefficients from the calculated yield response curves as well as the yields from the specific manure and cover crop treatments.

Apparent recovery of cover crop nitrogen (ANR) was calculated as suggested by Schröder et al. (1997).

$$ANR = 100 \times (NYcc - NYnc)/NYCC$$

where NYcc = nitrogen yield of unfertilized crop preceded by cover crop, NYnc = nitrogen yield of unfertilized crop preceded by no-cover crop, NYCC = aboveground nitrogen yield of the cover crop.

Soil Sampling and Analysis

Soil samples were collected every 2 wk from September to December 2003 and April to November 2004 from all treatments in each location. Soil samples were taken in 20-cm increments to a maximum depth of 80 cm. Soil samples were collected using either a standard 25-mm diam. soil probe or a machine sampling Concord 9800E soil coring unit and store at −17°C until analyzed. Four soil samples were collected from each plot when hand-sampled, two samples from the front and two from back of the plot. When soil samples were taken using the Concord 9800E, two 4.6-cm diam. cores were taken from front and back of the plot. The soil samples were extracted using 2 M KCl, according to Maynard et al. (2007), and analyzed for nitrate N and ammonium N using a Technicon TRAACS-800 Auto Analyzer (Tarrytown, NY).

Ammonia Volatilization Assay after Manure Application

Ammonia volatilization was measured only in plots with RC and no-cover crop at both the zero and higher manure N application rates, using 30-cm diam. inverted plastic chambers, fitted with Kitagawa NH_3 detector tubes which measure NH_3–N in μL L^{-1} (North Tech Workholdings Inc., Schaumburg, IL), for the first two measurements and Gastec passive dosimeter tubes which measure NH_3–N in μL L^{-1} per hour (Kiwa Gastec Technology, Apeldoorn, the Netherlands) for remainder. Plastic chambers were placed immediately after manure application, and NH_3 volatilization was measured 1 h, 1d, 3d, 7d, 14 d, and until the NH_3 volatilization stopped. Correction factors for temperature (provided by the manufacturer) were used to adjust for temperature differences. Ammonia losses were recorded as average hourly concentrations of NH_3 above individual plots.

Statistical Analysis

Data were statistically analyzed as a two-factor factorial experiment with the three manure application rates and six cover crop treatments and including the split N fertilizer rates as a split plot ($n = 4$). Manure application rates and six cover crop treatments were considered the main plot and the N fertilizer rates (0 and 200 kg N ha^{-1}) as the split plot. Data were analyzed using an ANOVA appropriate for a split plot design using the Proc Mixed procedure of SAS version 8.02 (SAS Institute, Cary, NC). Within each cover crop, the effect of manure application rate on each response variable measured using linear and nonlinear contrasts. Effect of different manure N rates applied and cover crops on succeeding corn was also identified using linear and nonlinear contrasts. Differences within cover crops and manure application rates were analyzed using LSD at $P < 0.05$ level. Effect of cover crops, manure N application, and N fertilizer rates on total soil mineral N was analyzed using Proc Mixed procedure. Since soil samples analyzed at 20-cm increments down to 60 cm were not statistically significant, depth was divided into 0- to 60- and 60- to 80-cm increments representing the root zone and below the root zone. All the results were expressed at significance levels of $P < 0.05$.

RESULTS

Cover Crop Biomass and Nitrogen Uptake

Cover crop biomass of non-legume species positively responded to manure application in fall of 2003. Cover crop biomass increased (perennial ryegrass–130 to 110%, oilseed radish–130%, and oat–90 to 110%) at the high-manure application rate at Elora and St. Mary's in comparison to no-manure application (Table 2). Red clover response to manure was much less. Only a 25% increment in biomass was found in fall-killed RC at high-manure application rate. Among the spring-killed cover crops, at high-manure application rate perennial ryegrass had greater biomass increment (50–100%) than RC (0–25%). Cover crop N uptake response to manure application rates was similar to the response observed for cover crop biomass. Cover crop N uptake was higher at the high-manure application rate compared to the no-manure application, especially in non-legumes. Oat and perennial ryegrass (fall) had greater N recovery (20–25%) than oilseed radish (15%) and RC (6–8%) at both sites. Among the spring-killed cover crops, perennial ryegrass had greater N recovery (10–25%) than RC (0–3%).

Cover Crop Effect on Ammonia Volatilization

Ammonia losses were not observed from the no-cover crop treatments and RC treatments with no-manure applied (data not shown). At both Elora and St. Mary's, 1 h after manure applied, ammonia losses were significantly greater from the treatment with manure applied to the RC (14 and 22 μL L^{-1} NH_3 at Elora and St. Mary's respectively) than the incorporated manure with no-cover crop treatment (2 and 0 μL L^{-1} NH_3 at Elora and St. Mary's respectively). After the first hour, differences were no longer significant and NH_3 levels were minimal at both sites. Following manure application, NH_3 volatilization was not detected after 16 d at Elora and 22 d at St. Mary's.

Cover Crop × Manure Effects on Corn

6–8 Leaf Stage–Corn Biomass and Nitrogen Uptake: Corn biomass production at the 6–8 leaf stage was affected by the cover crop type, where manure application did not have an impact at either location (data not shown). Among the different cover crop treatments used, generally highest corn biomass production was observed with the fall-killed RC (110–220 kg ha^{-1}), where lowest with perennial ryegrass (80–130 kg ha^{-1}). Similarly corn N uptake was lower with

Table 2. Cover crop biomass (dry weight.) and nitrogen content in the biomass as affected by cover crop and manure application rate at Elora and St. Mary's in the 2003–2004 growing season.

Location	Manure rate	Fall 2003				Spring 2004	
		RC-F†	OR‡	PRG§	Oat	RC-S¶	PRG
	kg N ha^{-1}	Biomass, kg ha^{-1}					
Elora	0	1930a#	570c	1180b	1340b	1760a	1200b
	134	1860a	1090b	2250a	2390a	2510a	1500b
	266	2380a	1290b	2700a	2520a	2240a	1800a
	Mean	2060v	980w	2040v	2080v	2170v	1500v
Contrasts††	Linear	ns‡‡	*	*	*	ns	ns
	Nonlinear	ns	ns	ns	ns	ns	ns
St. Mary's	0	980a	n/a§§	500b	400b	2120a	1550b
	64	520ab	80b	720a	750a	2340a	1720b
	128	1230a	90b	1070a	850a	2060b	3120a
	Mean	910v	60x	760vwx	670w	2170v	2130v
Contrasts	Linear	ns	ns	ns	ns	ns	*
	Nonlinear	ns	ns	ns	ns	ns	ns
		Nitrogen in biomass, kg N ha^{-1}					
Elora	0	42ab	14d	27bc	32bc	59a	32b
	134	52b	38c	65a	74a	73a	41b
	266	63b	51c	92a	95a	67a	58a
	Mean	52w	34x	61v	67v	67v	44w
Contrasts	Linear	*	*	*	*	ns	*
	Nonlinear	ns	ns	ns	ns	ns	ns
St. Mary's	0	28a	n/a	19a	15a	69a	40b
	64	15bc	4c	25ab	32a	74a	38b
	128	35a	4b	43a	39a	64a	75a
	Mean	26v	3w	29v	29v	69v	51w
Contrasts	Linear	ns	na	*	*	ns	*
	Nonlinear	*	na	ns	ns	ns	ns

* Significant at the 0.05 probability level.
† RC-F, red clover fall killed.
‡ OR, oilseed radish.
§ PRG, perennial ryegrass.
¶ RC-S, red clover spring killed.
# Letters within manure application rates or means, values followed by the same letter are not significantly different ($P \leq 0.05$) from one another.
†† Linear and nonlinear contrasts indicate trends within cover crop treatments.
‡‡ ns, not significant at the 0.05 level.
§§ na, mean not available due to missing value.

perennial ryegrass treatment (3 kg N ha^{-1}), compared to the fall-killed RC treatment (9 kg N ha^{-1}) at Elora.

Silking Stage–Corn Biomass and Nitrogen Uptake: At the 0 kg N ha^{-1} fertilizer rate, all the cover crops treatments increased corn biomass production with increasing manure application rate at Elora (data not shown). Mean corn biomass production following the perennial ryegrass (6180 kg ha^{-1}) was lower than following all the other cover crop treatments (7250–7670 kg ha^{-1}), at the 0 kg N ha^{-1} rate. At the 200 kg N ha^{-1} fertilizer rate, corn biomass of all the cover crop treatments tended to be higher, with no significant difference among the effect of cover crop treatments (data not shown). Corn biomass production following the RC treatments was generally higher at both 0 and 200 kg N ha^{-1} fertilizer rate at St. Mary's (data not shown). Corn N uptake was lower with the perennial ryegrass treatment than the other cover crop treatments under the both N fertilizer rates (data not shown). Further, at 0 kg N ha^{-1} fertilizer rate, highest corn N uptake was found with the RC treatments compared to the other cover crop treatments, but at 200 kg N ha^{-1} fertilizer rate N uptake of corn following the non-legume cover crops also increased in both sites. Generally, highest corn N uptake was associated with the high-manure N application rate at both the N fertilizer rates at Elora and with 0 kg N ha^{-1} fertilizer rate at St. Mary's.

Harvesting Stage–Grain Yield and Nitrogen Content: At the 0 kg N ha^{-1} fertilizer rate, non-legume cover crop treatments, including the no-cover crop treatment, typically had significant increases in corn grain yield and grain N content with increasing manure N rate at Elora (Table 3). Increasing manure N rates did not increase corn yield or grain N content for either RC treatment at either location. Corn grain N content following the oilseed radish and perennial ryegrass positively responded to manure N application rate at Elora, for the 200 kg N ha^{-1} fertilizer rate. At St. Mary's, only oilseed radish showed significant increment in grain yield and grain N content with increasing manure N rate under the 0 kg N ha^{-1} fertilizer rate. At both locations, corn grain yield

Table 3. Corn grain yield and grain N content at harvest as affected by manure application rate, cover crop and N fertilizer rate. Linear and nonlinear contrasts indicate trends within cover crop treatments.

Location	Manure rate	Grain yield, t ha^{-1}							Grain N content, kg N ha^{-1}						
		NC†	RC-F‡	RC-S§	OR¶	PRG#	Oat	Mean	NC	RC-F	RC-S	OR	PRG	Oat	Mean
	kg ha^{-1}														
					0 kg N ha^{-1}							0 kg N ha^{-1}			
Elora	0	9.2	11.3	11.0	8.8	7.9	9.0	9.5c††	83	126	127	80	70	85	96c
	134	9.6	11.4	11.0	10.4	8.9	9.9	10.2b	87	136	132	108	86	95	107b
	266	11.0	11.6	11.4	10.8	9.7	11.3	11.0a	105	141	139	116	104	126	122a
	Mean	9.9v	11.4u	11.1u	10.0v	8.9w	10.1v		92vw	135u	133u	101v	87w	102v	
Contrasts‡‡	Linear	*	ns§§	ns	*	*	*		*	ns	ns	*	*	*	
	Nonlinear	ns	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	
					200 kg N ha^{-1}							200 kg N ha^{-1}			
Elora	0	12.0	11.2	11.9	11.3	10.5	11.5	11.4a	143	141	145	133	120	138	137b
	134	12.0	10.8	11.4	11.8	10.8	11.2	11.3a	148	137	134	143	135	137	139b
	266	12.1	11.3	11.6	12.3	11.4	11.1	11.6a	155	142	148	153	148	132	146a
	Mean	12.0u	11.1wx	11.6uvw	11.8uv	10.9x	11.3vwx		149uv	140v	142uv	143uv	135w	136vw	
Contrasts	Linear	ns	ns	ns	ns	ns	ns		ns	ns	ns	*	*	ns	
	Nonlinear	ns	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	
					0 kg N ha^{-1}							0 kg N ha^{-1}			
St. Mary's	0	6.2	7.8	8.8	6.1	6.2	6.8	7.0a	56	74	96	55	58	63	67a
	64	6.7	7.3	8.6	7.1	5.8	8.3	7.3a	61	68	94	70	55	86	72a
	128	7.4	7.8	8.3	7.4	6.3	7.1	7.4a	72	77	90	73	59	79	75a
	Mean	6.8wx	7.7v	8.5u	6.9w	6.1x	7.4vw		63vw	73v	93u	66vw	57w	76w	
Contrasts	Linear	ns	ns	ns	*	ns	ns		ns	ns	ns	*	ns	ns	
	Nonlinear	ns	ns	ns	ns	ns	*		ns	ns	ns	ns	ns	ns	
					200 kg N ha^{-1}							200 kg N ha^{-1}			
St. Mary's	0	10.0	10.0	9.9	9.9	9.3	9.9	9.8a	126	120	121	122	114	122	121a
	64	10.4	9.9	10.0	9.5	8.9	9.8	9.8a	126	123	124	117	124	123	123a
	128	9.7	9.0	9.3	9.4	9.9	9.2	9.4a	125	110	117	113	117	116	116a
	Mean	10.0u	9.6u	9.7u	9.6u	9.4u	9.7u		126u	118v	120uv	117v	118v	120uv	
Contrasts	Linear	ns	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	
	Nonlinear	ns	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	

* Significant at the 0.05 probability level.

† No-cover crop.

‡ RC-F, red clover fall killed.

§ RC-S, red clover spring killed.

¶ OR, oilseed radish;

PRG, perennial ryegrass.

†† Letters within means, values followed by the same letter are not significantly different ($P \leq 0.05$) from one another.

‡‡ Linear and nonlinear contrasts indicate trends within cover crop treatments.

§§ ns, not significant at the 0.05 level.

following the RC treatments was higher compared to the other cover crop treatments, under the 0 kg N ha^{-1} fertilizer rate. Similarly, grain N content was higher with both RC treatments at Elora, where only spring-killed RC treatment had higher corn grain N content at St. Mary's compared to the other cover crop treatments. At 200 kg N ha^{-1} fertilizer rate, generally corn following the non-legume cover crops also had high grain yield and grain N content similar to corn following RC at both locations.

Harvesting Stage–Corn Stover Biomass and Nitrogen Uptake: Generally at 0 kg N ha^{-1} fertilizer rate, corn following perennial ryegrass had lower biomass yield and tissue N content compared to the other cover crops at both the locations (Table 4). At Elora, corn following the RC treatments had higher biomass yield (6.2–6.2 t ha^{-1}) and tissue N content (49–52 kg N ha^{-1}), compared to the other cover crops (4.9–5.9 t ha^{-1} and 36–43 kg N ha^{-1}) at the 0 kg N ha^{-1} fertilizer rate. However, at 200 kg N ha^{-1} fertilizer rate, corn biomass and tissue N content of the corn following the non-legume crops were comparable to corn following RC at both the locations. At Elora, highest tissue N content in corn biomass was found with high-manure application rate under the two N fertilizer rates.

Corn Response to Nitrogen Fertilizer and Cover Crop Fertilizer Nitrogen Equivalent

At the 6–8 leaf stage and silking stage, corn biomass increased from 0 to 50 kg N ha^{-1} fertilizer and did not increase with further increases of N fertilizer (data not shown). However, at the grain harvest stage corn grain yield increased following a quadratic plateau function ($R^2 = 0.67$, $Y = 9345 + 43.28X - 0.1516X^2$) at Elora, where at St. Mary's, yield data fitted a quadratic function that did not reach a maximum over the range of N fertilizer rates applied ($R^2 = 0.55$, $Y = 7468 + 18.11X - 0.0235X^2$). The most economical rate of N application, based on a current price ratio of 10 is 110 and 173 kg ha^{-1} at Elora and St. Mary's, respectively.

Cover crop treatments without additional N fertilizer generally resulted in grain yields lower than the fitted response

Table 4. Corn stover biomass (dry wt.) and nitrogen uptake at harvest as affected by manure application rate, cover crop and nitrogen fertilizer rate at Elora and St. Mary's. Linear and nonlinear contrasts indicate trends within cover crop treatments.

Location	Manure rate	Corn stover biomass, t ha^{-1}							Corn biomass N content, kg N ha^{-1}						
		NC†	RC-F‡	RC-S§	OR¶	PRG#	Oat	Mean	NC	RC-F	RC-S	OR	PRG	Oat	Mean
	kg ha^{-1}	kg ha^{-1}							kg ha^{-1}						
		0 kg N ha^{-1}							0 kg N ha^{-1}						
Elora	0	5.6	6.0	6.4	5.2	4.5	5.3	5.5b††	37	47	50.	33	30	36	39b
	134	5.9	6.4	6.3	6.4	5.2	5.7	6.0a	39	52	50	40	37	38	43b
	266	6.2	6.2	6.2	5.7	5.1	6.9	6.1a	40	48	57	42	39	56	47a
	Mean	5.9u	6.2u	6.3u	5.8v	4.9w	5.9v		39vw	49u	52u	38vw	36w	43v	
Contrasts‡‡	Linear	ns§§	ns	ns	ns	ns	*		ns	ns	ns	ns	ns	*	
	Nonlinear	ns	ns	ns	*	ns	ns		ns	ns	ns	ns	ns	*	
		200 kg N ha^{-1}							200 kg N ha^{-1}						
Elora	0	6.9	6.6	6.2	6. 0	6.3	6.7	6.4a	55	63	52	50	56	54	55b
	134	6.9	6.2	6.0	7. 0	5.9	6.7	6.5a	62	55	54	58	43	57	55b
	266	6.6	6. 6	6.6	7.2	6.0	6.9	6.7a	61	64	63	61	54	64	61a
	Mean	6.9u	6. 5vw	6. 3w	6.7uv	6.1w	6.8uv		60u	61u	56uv	56uv	51v	58u	
Contrasts	Linear	ns	ns	ns	*	ns	ns		ns	ns	*	*	ns	*	
	Nonlinear	ns	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	
		0 kg N ha^{-1}							0 kg N ha^{-1}						
St.	0	3.8	4.9	5.4	4.1	4.3	4.3	4.5a	28	38	50	26	33	31	35a
Mary's	64	4.8	4.6	5.1	4.5	4.1	5.5	4.8a	31	36	44	38	27	44	37a
	128	4.5	4.7	5.3	4.8	4. 0	4.9	4.7a	34	46	45	39	30	44	40a
	Mean	4.4vw	4.8uvw	5.2u	4.5vw	4.1w	4.9uv		31vwx	40uv	46u	35vwx	30wx	39uvw	
Contrasts	Linear	ns	ns	ns	*	ns	ns		ns	ns	ns	*	ns	*	
	Nonlinear	ns	ns	ns	ns	ns	*		ns	ns	ns	ns	ns	ns	
		200 kg N ha^{-1}							200 kg N ha^{-1}						
St.	0	6.1	6.3	6.3	5.8	5.8	6.3	6.1a	62	66	68	61	64	64	64a
Mary's	64	6.2	6.0	5.7	5.6	5.5	6.6	5.9a	60	64	62	55	57	69	61a
	128	6.2	5.7	5.7	6.2	5.3	5.7	5.8a	64	54	60	68	60	59	61a
	Mean	6.2uv	6.0uv	5. 9uv	5.9uv	5.5v	6.2u		62u	61u	63u	61u	60u	64u	
Contrasts	Linear	ns	ns	ns	ns	ns	ns		ns	*	ns	ns	ns	ns	
	Nonlinear	ns	ns	ns	ns	ns	ns		ns	ns	ns	ns	ns	ns	

* Significant at the 0.05 probability level.
† No-cover crop.
‡ RC-F, red clover fall killed.
§ RC-S, red clover spring killed.
¶ OR, oilseed radish.
# PRG, perennial ryegrass.
†† Letters within means, values followed by the same letter are not significantly different ($P \leq 0.05$) from one another.
‡‡ Linear and nonlinear contrasts indicate trends within cover crop treatments.
§§ ns, not significant at the 0.05 level.

curve. However, cover crop treatments with manure N and also additional N fertilizer had grain yields greater than the fitted response curve at St. Mary's (data not shown).

With the no-manure N treatment, FNE for legumes and non-legumes were significantly different at Elora, ($P < 0.05$; Fig. 2a). At the low-manure N application, fall-killed RC treatment had significantly higher FNE values compared to all the other non-legume cover crop treatments. However, at the high-manure application rate, there were no significant differences among the cover crop treatments, with the exception of perennial ryegrass which had a significantly lower FNE. Fertilizer N equivalent increased with the addition of manure N. For perennial ryegrass the FNE was less than that for the no-cover crop treatment. At St. Mary's, spring-killed RC treatment had significantly higher FNE than the non-legume cover crops under low manure N rates (Fig. 2b). At the high-manure N application rate, spring-killed RC had higher FNE than the no-cover crop, fall-killed RC and perennial ryegrass treatments. Similar to Elora, perennial ryegrass had lower FNE compared to the other cover crop treatments at St. Mary's.

Apparent Recovery of Cover Crop Nitrogen

On average, apparent nitrogen recovery (ANR) by corn was higher in fall-killed RC (100–130%) and spring-killed RC (90–100%) compared to the non-legume cover crops (–60–60%) with no manure application at St. Mary's and Elora respectively (data not shown). Generally at high-manure rate, N recovery by corn was decreased from fall-killed RC (50–70%) and spring-killed RC (50–80%) at St. Mary's and Elora, respectively. Opposite trend was found with non-legumes especially at Elora, where corn recovered more N from non-legumes grown under high-manure application (–2–40%) than the non-legumes grown without manure (–60–4%). Nitrogen recovery from perennial ryegrass was lowest among the all the cover crops at both high-manure (–23 to –2%) and no-manure application rates (–58–18%) at St. Marys' and Elora, respectively.

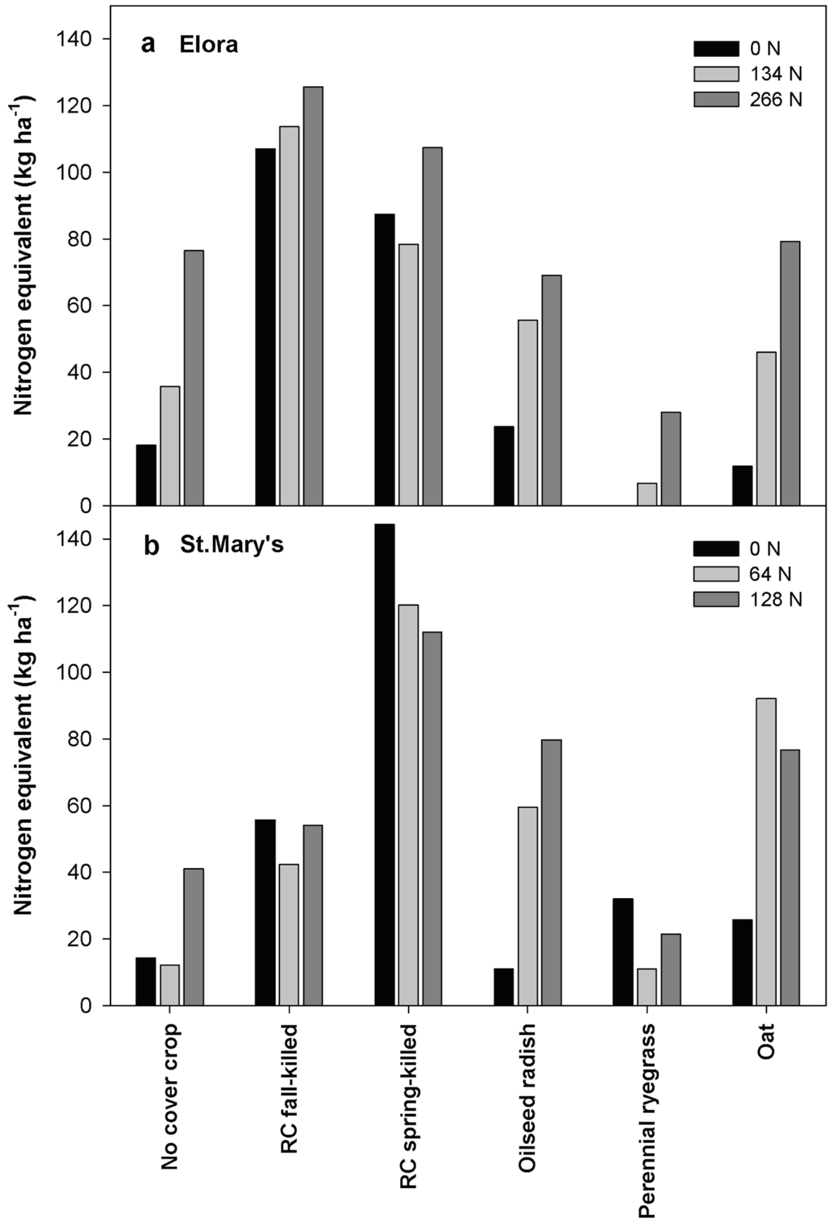

Fig. 2. Manure N application rate and cover crops treatment effects on fertilizer nitrogen equivalent (FNE) for corn grain yield at (a) Elora and (b) St. Mary's. RC, red clover; N, manure nitrogen application rate in kg N ha^{-1} LSD = 55 kg ha^{-1} for the pair wise comparison between cover crops within manure application rates.

Cover Crop × Manure Effect on Soil Total Mineral Nitrogen

Soil Mineral Nitrogen–Fall, 2003: During 2003 fall, in the 0- to 60-cm depth, cover crop type and the manure application rate had a significant effect on total soil mineral N level at both Elora and St. Mary's (Table 5). Generally RC treatments had lower mineral N levels than the other cover crop treatments. Oilseed radish and perennial ryegrass treatments also had lower soil mineral N similar to RC treatments on 14 November. At St. Mary's, during 2003 fall, lower soil mineral N levels were found with the RC treatments in all sampling dates, other than the 30 October sampling. Perennial ryegrass treatment also had lower soil mineral N level on 20 November similar to RC treatments. Generally, the no-cover crop treatment had the highest mineral N at both the locations. Soil mineral N levels increased with manure application rates at both locations. At Elora, in the 60- to 80-cm soil depth, RC treatments had lower soil mineral N at no-manure application and highest at the high-manure rate ($P < 0.001$; data not shown). Similar to 0- to 60-cm soil depth, mineral N levels in 60- to 80-cm soil depth increased with manure application rates at Elora (14 Nov. 2003) and St. Mary's (30 Oct. 2003) ($P < 0.05$; data not shown).

Soil Mineral Nitrogen–2004: In 2004, at 0- to 60-cm soil depth, soil mineral N was mainly affected by the cover crop type at both Elora and St. Mary's (Table 5). At Elora, fall-killed RC treatment had higher soil mineral N level compared to the non-legume treatments, especially perennial ryegrass. Soil mineral N level increased in spring-killed RC treatment same as the fall-killed RC treatment during June and July 2004 at Elora (Table 5). Similar trend was found at St. Mary's with the spring-killed RC for the soil mineral N at 0- to 60-cm soil depth. Fall-killed RC treatment had higher soil mineral N during the spring (3 and 18 May 2004), where spring-killed

Table 5. Total soil mineral nitrogen (kg N ha^{-1}) in the 0- to 60-cm layer of soil over the 2003–2004 growing season at Elora and St. Mary's.

		Total mineral N, kg N ha^{-1}												
		2003				2004								
Location	Main effect	16 Sept.	6 Oct.	23 Oct.	14 Nov.	12 Apr.	26 Apr.	10 May	26 May	9 June	21 June	19 July	1 Sept.	18 Nov.
Elora	Manure N rate													
	0	47c†	29c	33c	30c	59	25b	32b	37	82	82b	68	33	29
	134	84b	51b	54b	39b	59	30b	36b	38	100	91ab	70	32	26
	266	117a	89a	74a	55a	55	40a	47a	42	96	94a	75	31	29
	F probability	***	***	***	***	ns‡	***	***	ns	ns	*	ns	ns	ns
	Cover crop													
	NC§	108a	83a	86a	57a	48	33bc	45a	39ab	85ab	80c	56b	23b	29
	RC-F¶	58b	31d	45bc	35bc	55	40a	52a	48a	110a	120a	96a	46a	32
	RC-S#	56b	49cd	60b	40bc	51	27c	27b	42ab	98a	107b	96a	40a	33
	OR††	96a	58bc	60b	45b	60	39ab	43a	38bc	111a	87c	65b	27b	25
	PRG‡‡	95a	50bcd	31c	35bc	46	17d	17b	29c	68b	62d	57b	30b	24
	Oat	83ab	69ab	39c	33c	85	35ab	45a	38bc	86ab	81c	56b	29b	25
	F probability	**	***	***	***	ns	***	***	**	*	***	***	***	ns
St. Mary's	Manure N rate	25 Sept.	14 Oct.	30 Oct.	20 Nov.	20 Apr.	3 May	18 May	1 June	14 June	28 June	26 July	14 Sept.	29 Nov.
	0	79c	40b	71	32b	37b	29	43	47	59	56	53	27	19
	64	98b	48a	75	39ab	42a	32	54	47	60	60	55	25	21
	128	125a	56a	84	45a	42a	34	49	47	66	62	60	33	24
	F probability	***	**	ns	*	*	ns	ns	ns	ns	ns	ns	ns	ns
	Cover crop													
	NC	110a	57a	86a	46a	40a	35a	49bc	43bc	58	56bc	46b	24	21b
	RC-F	82b	35c	82ab	34b	43a	40a	61a	47abc	63	57bc	54b	33	19b
	RC-S	84b	41bc	56c	32b	41a	23b	44bc	57a	69	76a	80a	35	31a
	OR	115a	52ab	86a	51a	43a	38a	54ab	44abc	65	56bc	51b	24	16b
	PRG	114a	54a	70bc	31b	31b	19b	37c	36c	47	47c	53b	27	21b
	Oat	99a	48abc	80ab	39ab	46a	34a	49bc	53ab	65	63b	52b	26	20b
	F probability	**	**	**	*	***	***	*	*	ns	**	***	ns	**

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Individual sample dates analyzed separately and letters followed by the same letter are not significantly different ($P \leq 0.05$) from one another.
‡ ns, not significant at the 0.05 level.
§ No-cover crop.
¶ RC-F, red clover fall killed.
# RC-S, red clover spring killed.
†† OR, oilseed radish.
‡‡ PRG, perennial ryegrass.

RC treatment had higher mineral N during the summer 2004, compared to other cover crop treatments (Table 5). Mineral N levels of the oilseed radish and oat treatments were comparable with the no-cover crop treatment at 0- to 60-cm soil depth at both the locations (Table 5). At 0- to 60-cm soil depth, soil mineral N levels increased with manure application rate was observed on three sampling dates at Elora (26 Apr., 10 May, and 21 June 2004) and one sampling date at St. Mary's (4 Apr. 2004).

At Elora, in the 60- to 80-cm soil depth, oat treatment had significantly higher soil mineral N level compared to the perennial ryegrass treatment on 10 May, 26 May, and 6 June 2004 (data not shown). Red clover treatments had higher soil mineral N levels than the no-cover crop treatment at 0 and 256 kg N ha^{-1} rates (18 Nov. 2004). At St. Mary's, in the 60- to 80-cm soil depth, oilseed radish had higher soil mineral N level compared to the spring-killed RC treatment (20 Apr. and 3 May 2004). Manure application rate did not have significant effect on soil mineral N at St. Mary's, where it increased with manure application rate at Elora, only on 5 Apr. 2004.

DISCUSSION

Cover Crop Response to Manure Application

Biomass accumulation of the fall cover crops at Elora ranged from 570 to 2700 kg ha^{-1}, whereas it was lower in St. Mary's, ranging from 80 to 1230 kg ha^{-1} (Table 2). The cover crop biomass production at Elora was comparable to previous cover crop biomass levels reported in southern Ontario (Vyn et al., 1999, 2000). Lower levels of fall biomass production in St. Mary's were primarily due to poor establishment of cover crops resulting from dry soil conditions at the time of planting. At St. Mary's no rainfall was received 10 d after the seeding. Although spring-killed yield of perennial ryegrass and red clover was low (760–910 kg ha^{-1}) at St. Mary's, they recovered during the spring of 2004 and produced high yield (2130–2170 kg ha^{-1}) similar to yield at Elora.

Generally non-legume cover crops had a greater positive response to manure application than RC in terms of biomass and N uptake. In comparison to no-manure application, biomass increment (%) of non-legumes at the high-manure application rate was greater (50–130%) than the RC treatments (0–25%). This is consistent with previous observations that non-legume biomass positively responds to N application (Vyn et al., 1999; King et al., 2012), and the response is greater than observed for legumes such as RC (Xia and Wan, 2008). In comparison to no-manure application, fall-killed non-legumes increased their N uptake at Elora (200–260%) and St. Mary's (130–150%) at the high-manure application rate. Red clover had poor response to manure application where only up to 50% increase in N uptake was found at the high-manure application rate compared to the no-manure application. Generally manure N recovery ranged 0 to 25% among the different cover crop treatments. Among all of the cover crops, RC had lower N recovery (0–8%). These findings reveal that RC was not efficient in capturing the fall-applied manure N, where non-legume cover crops were also still not efficient in capturing the applied manure N. Since manure was not incorporated into the soil after applying to RC, N losses through NH_3 volatilization and runoff were possibly higher for RC compared to the non-legume treatments where manure was incorporated into the soil. Also the majority of RC N requirement may be met through symbiotic N fixation (Thilakarathna et al., 2012), and only a small proportion of its N requirement may be derived from the soil, thus efficiency in recovering applied manure N may be lower.

Cover Crop Effect on Ammonia Volatilization Losses of Manure Nitrogen

Cover crops established before manure application do not allow for incorporation of manure. In the current study, manure was incorporated within 15 min of manure application to all cover crop treatments except RC. Ammonia losses were significantly greater where manure was not incorporated on the RC treatments, which corroborates results of Rochette et al. (2001). Manure ammonium can be released quickly into the atmosphere if not incorporated immediately (Webb et al., 2014). In the current study, N losses from the non-incorporated manure occurred within a very short period following manure application, thereby demonstrating the importance of rapid manure incorporation. Similar to Sommer and Hutchings (2001), we observed that NH_3 volatilization is low 1 h after manure application. Unfortunately the methodology used to detect ammonia losses in this study does not enable a per unit area quantification of N losses. According to the weather data, mean temperature was 15.2 and 17.5°C at Elora and St. Mary's respectively on the manure application dates, and minimal rain was received for 12 d after manure application. Therefore, N losses due to leaching and runoff were low immediately following manure application.

Cover Crops Effect on Corn

Corn has a harvest index of approximately 50% (Liu et al., 2004). Our reported harvest indexes were higher (60–64%) when Tables 3 and 4 data are considered. The discrepancy is due to cobs and husk weight not being included into total biomass and plants, and also because plants were harvested at 15 cm cutting height instead of ground level. At Elora, where manure rates were significantly higher than St. Mary's, corn biomass, grain yield, and N uptake were increased by increasing manure rate especially following the non-legumes. Although the same trend was found at St. Mary's, it was not possible to demonstrate statistical significance. In the absence of cover crop (no-cover crop treatment), manure application did not improve the corn biomass at St. Mary's. Lack of significant effect, suggests the possibility of significant N losses from the system when manure is fall applied. Total precipitation from September 2003 to April 2004 was greater at St. Mary's (857 mm) than Elora (591 mm) (Fig. 1). This can possibly lead to more N losses from the applied manure at St. Mary's through nitrate leaching and runoff.

It has commonly been suggested that use of a cover crop following manure application will result in N sequestration by the cover crop (Singer et al., 2008; Cambardella et al., 2010) and subsequent mineralization and release to the following crop. Our results indicate that the cover crops were not effective in conserving N in this manner. For perennial ryegrass, oat or oil seed radish, there was no evidence that they were effective at "transferring" N from fall-applied manure to the subsequent corn crop. Corn biomass, yield, or N uptake response to manure application was not increased using these cover crops in comparison to no cover crop treatment. This result is consistent with our findings that these cover crops had no significant impact on soil mineral N during the period corresponding with corn N uptake.

When RC was used as a cover crop following manure application, corn biomass, grain yield, and N uptake were higher than the no cover crop treatment, as well as other cover crop treatments. This effect was observed at all manure application rates, and was greatest at the zero manure application rate. This effect was observed for both fall-killed and spring-killed RC. This observation is consistent with our cover crop N uptake data that indicates that RC maintains greater biomass and N content across a range of manure application rates. Based on the apparent N recovery data it confirmed that corn was able to recover more N from RC than the other cover crops, which corroborates the findings of Schröder et al. (1997). It further corresponds with our observation that the N mineralization pattern of fall and spring killed RC corresponds most closely with the N uptake pattern of corn.

At the zero corn N rate, corn yield and FNE following RC were greater than the no cover treatment, corn yield, and FNE following oilseed radish and oat were similar to the no cover crop treatment, and corn yield and FNE following perennial ryegrass were lower than the no cover treatment (Elora). The comparative yield results across cover crop species are consistent with observations in previous studies (Vyn et al., 1999). Based on soil N data, and corn response, perennial ryegrass appears to immobilize soil mineral N. As C/N ratio of the perennial ryegrass was higher (15–19:1) than the other cover crops (10–17:1) (data not shown), it possibly requires a longer time for mineralization. Alternatively, perennial ryegrass may cause additional non-N effects such as allelopathy (Sutherland et al., 1999), which may reduce the nitrification rate by inhibiting nitrifying bacteria (Alsaadawi et al., 1986). There is some indication of allelopathy since, the perennial ryegrass treatments tended to be associated with lower corn yields even when corn was fertilized at the 200 kg N ha^{-1} rate. Previous studies also have shown the lower corn yield and N uptake following ryegrass (Dapaah and Vyn, 1998; Vyn et al., 1999), possibly due to the N immobilization and slow N mineralization by perennial ryegrass (Elgersma and Hassink, 1997).

Other than the possible negative effect by allelopathy in perennial ryegrass, we did not observe any positive non-N benefits of using cover crops. At the 200 kg N ha^{-1} rate for corn, corn yields of all other cover crop treatments were equal to or less than corn yield following no cover crop. At Elora, corn yield at the 200 kg N ha^{-1} rate following RC were lower than the no cover crop treatment, indicating a possible negative N effect which may be due to the high N rate resulting from the combined N from RC N, manure N and 200 kg N ha^{-1} corn N fertilizer. Greater N recovery by corn from RC was possibly due to their N fixation and rapid turnover of tissue N for the following crop. It should be noted that this trial evaluated a "single use" of cover crops and non-N benefits associated with cover crops, such as improvements in soil structure, may only be apparent after several years of repeated use especially in non-legume cover crops.

Cover Crops × Manure Effect on Soil Mineral Nitrogen

Soil Mineral Nitrogen–Fall 2003 following Manure Application: Earlier depression of soil mineral N by RC in comparison to other cover crops may be due to rapid RC stand establishment and N uptake, since RC was established in the spring as an underseed to a cereal crop. On the other hand earlier depression of soil mineral N may also be due to higher ammonia losses associated with the RC treatments. Since manure applied to the RC treatments was not incorporated, lower soil mineral N levels could be related to the increased loss of NH_3 following manure application (Webb et al., 2010).

Perennial ryegrass and oat were also effective in reducing soil mineral N levels in the fall following manure N application. The level of reduction appeared to correspond with the amount of biomass produced by these species. At Elora, where biomass production was greater, the effect of these crops on soil mineral N was more consistent and larger. Perennial ryegrass and oat did not reduce soil mineral N levels in comparison to the no cover treatment early in the fall, when biomass levels of these species were lower. However, later in the fall when these species had higher levels of biomass, significant reductions were observed particularly at high-manure application rates. From late October, there were significant decreases in the soil mineral N levels with the perennial ryegrass and oat treatments compared with no cover treatment. Perennial ryegrass and oat reduced the amount of soil mineral N reaching the 60- to 80-cm depth suggesting that these species were effective for reducing N leaching in the late fall. In general, the no-cover crop treatment had higher soil mineral N at most depths relative to all other cover crop treatments.

Soil Mineral Nitrogen–2004 Corn Growing Season: Corn N uptake occurs from the onset of vegetative growth into the grain-fill period (Rajcan and Tollenaar, 1999). Uptake of N during vegetative stages is correlated with leaf area and biomass accumulation, consequently during early stages of corn growth N uptake is minimal (Bender et al., 2013). Soil N before and after the period of maize N uptake is subject to increased risk of loss. In the present study soil mineral N measured from 9 June to 26 July roughly corresponds with the period during which corn uptake of N is highest. The amount of soil nitrate taken up by corn after 1 September in Ontario is probably low.

Manure application tended to elevate soil mineral N before this period. Manure application rate and cover crop did not interact indicating that soil mineral N increases occurred similarly across all cover crop treatments. Cover crop treatments however did differ in their effect on soil mineral N before this period. Perennial ryegrass and spring-killed RC treatments had reduced soil mineral N. Both crops were actively growing during this period and taking up N. The oat cover crop numerically tended to increase soil mineral N levels early in the season, particularly at Elora, however the effect was not significant, but this tendency is in agreement with observations by Vyn et al. (1999). Soil mineral N measurements at 60- to 80-cm soil depth taken from the spring-killed RC treatment tended to be lower than the fall-killed treatment, further suggesting that RC killed in the spring has the potential to reduce nitrate leaching during the spring period.

During the 9 June to 26 July period approximately corresponding with corn N uptake, again the effect of the various cover crop treatments were similar across manure application rates. Oat and oilseed radish had soil mineral N levels similar to the no cover crop treatment. Oat residue may have mineralized and released N before this period as suggested above by the tendency for elevated levels of N earlier in the season (Malpassi et al., 2000). Relatively low oilseed radish biomass as well as early season mineralization (Vyn et al., 1999) may explain low soil mineral N levels associated with the oilseed radish cover crop. Soil mineral N levels of the RC treatments were higher than the no cover crop treatment. The mineralization pattern of RC appeared to correspond favorably with the period of corn N demand. The spring-killed RC treatment had slower mineralization compared to the fall-killed RC treatment. Vyn et al. (2000) also found that spring-killed RC tended to have delayed soil NO_3–N concentrations compared to fall-killed RC. Compared to all the other cover crop treatments perennial ryegrass had the lowest mineral N level during the period of corn N uptake, similar to the results found by Vyn et al. (2000).

Following the period corresponding with corn N uptake, at Elora soil mineral N levels were higher for both the spring- and fall-killed RC in comparison to all other cover crops. At St. Mary's soil mineral N following corn harvest were elevated for the spring-killed RC cover crop. Although, RC appears to provide greater N benefit to corn compared to the other cover crops evaluated, it appears to cause greater risk of N loss following corn harvest. Following corn harvest, there was no evidence of release of N from the perennial ryegrass cover crop. This is interesting since, the perennial ryegrass treatment also did not have indications of elevated soil mineral N levels before or after the corn N uptake period. This is possibly due to the high C/N ratio in perennial ryegrass tissues, compared to the other cover crops, delaying the mineralization. The present study did not evaluate the impact of perennial ryegrass on soil mineral N 1 yr after control to determine if N is eventually released.

In summary, perennial ryegrass, oat, and RC were effective in reducing soil mineral N in the late fall after manure application. For RC, some of this reduction could be associated with higher ammonia losses due to inability to incorporate manure. Following corn harvest, soil nitrate was higher for spring-killed RC indicating greater risk of N loss. None of the cover crops evaluated were effective in transferring fall-applied manure N to corn grown the following growing season. Therefore, delaying manure application to spring may provide more available N during the growing season rather than applying in the fall with cover crops.

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