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Short-term persistence of ammonium-N following pig manure application is greater with perennial forage grasses than annual crops

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ABSTRACT

A 2-year study was conducted on a loamy sand soil to compare short-term persistence of ammonium-N in an annual (ACS) and a perennial (PCS) cropping system following pig manures application as a possible explanation for the reduced nitrate leaching from perennial forage grasses. In spring 2014 and 2015, nitrogen-based application rates of liquid (LPM) and solid (SPM) pig manure were broadcast on PCS and ACS plots with incorporation of the manures for ACS plots alone. Following manure applications, soil samples were taken at 0 - 15 and 15 - 30 cm depths on seven (2014) and six (2015) days over two to three weeks period for ammonium-N and nitrate-N concentrations. Ammonium-N (0 - 15 cm) with LPM peaked 4 d after manure application in ACS (18 - 29 kg ha⁻¹) and PCS (50 - 74 kg ha⁻¹) in both years. In both years, persistence of ammonium-N at 7 d was 46 - 77% in LPM amended PCS and 8 - 14% in LPM amended ACS. Ammonium-N measured in SPM amended ACS and PCS was low after manure application in both years. There was lower accumulation of nitrate-N in PCS than ACS of LPM and SPM amended treatments in both years. The greater persistence of ammonium-N in the LPM

amended PCS than ACS coupled with lower percentage increase in nitrate-N in the PCS may account for lower nitrate leaching previously observed for perennial forage grasses at the study location.

Keywords: Persistence, ammonium-N, nitrate-N, perennial cropping system, annual cropping system, pig manure.

Nitrogen (N) is an essential plant nutrient that is needed in relatively large amounts by plants to complete their life cycle and physiological activities (Delgado and Follett 2010). It is often the most limiting nutrient for crop growth (Malhi et al. 2001).

Pig manure is a source of N for plant uptake. In addition to the supply of N, pig manure increases organic matter composition, water holding capacity, wet aggregate stability, cation exchange capacity and decreases bulk density of soil (Darwish et al. 1995; Adesanya et al. 2016). With Manitoba being the largest pig producing and pig exporting province in Canada (Honey 2016), efficient management of pig manure is crucial for agronomic and environmental sustainability. Pig manure is mainly handled in slurry (> 90% water content by weight) or solid (< 80% water content by weight) forms. Slurry or liquid pig manure is the preferred form of pig manure storage in Canada (Dorff and Beaulieu 2014) because it is easier to handle than solid pig manure due to high level of dilution; although the high volume increases the cost associated with transportation and application (Vanotti et al. 2002; Bork et al. 2013). Relative quantities of the different forms of N in the pig manure depend on the method of manure collection, storage and handling, presence or absence of bedding materials and type of ration (Choudhary et al. 1996; Lamb et al. 2014). Solid pig manure has much of its N in the organic form and liquid pig manure

has a higher percentage of its N in the ammonium form (Schoenau and Davis 2006; Qian and Schoenau 2002).

If environmental conditions are not limiting, the ammonium in pig manure applied to soil is quantitatively converted to nitrate by soil microorganisms in a process known as nitrification (Sahrawat 2008). The nitrification process determines the relative quantities of ammonium and nitrate in the soil and the form of inorganic N taken up by plants and/or lost to the environment (Auyeung et al. 2015; Subbarao et al. 2015). It is influenced by environmental factors such as aeration, water content, pH, substrate and temperature (Barnard et al. 2005; Sahrawat 2008). The nitrification rate can range from 10 - 70 kg ha⁻¹ day⁻¹ under favourable temperature and moisture conditions when ammonium is not limiting (Bolado-Rodríguez et al. 2010). The nitrification process usually requires a pH range of 5.5 to 10 but it is optimum at pH of about 8.5 (Sahrawat 2008). It increases as the soil pH increases and decreases as the soil becomes acidified (Ste-Marie and Pare 1999). Nitrification of applied N in manure is affected by the method of application. van Es et al. (2006) reported that incorporation of manure promoted more rapid conversion of ammonium in manure to nitrate due to greater contact between soil microorganisms and ammonium and a high aeration level that enhances nitrification process. High concentrations of ammonium in soil may create a toxic zone to soil organisms and delay nitrification (Koper et al. 2010). Reports have shown that some ammonia oxidizers are sensitive to high ammonia concentration in soil (Norton 2008). In the case of perennial cropping system (PCS), manure is usually surface applied without incorporation and nitrification may be delayed due to high concentration of ammonium on the soil surface. This may in turn lead to a reduced nitrate-N accumulation in the subsoil. In annual cropping systems (ACS), incorporation of

manure following surface application may reduce the chance of a microbial toxic zones created by high ammonium concentration.

Studies have shown that PCS significantly reduced nitrate-N losses from leaching when compared to ACS (Entz et al. 2001; Thomsen 2005; van Es et al. 2006). Our three years field core lysimeter study that compared nitrate leaching between ACS and PCS that received pig manure showed that cumulative nitrate-N losses were significantly lower in PCS than ACS by harvest (Karimi et al. 2017). Soil samples collected at harvest in the plots where the lysimeters were located (the plots had the same treatment as the lysimeters) had higher soil nitrate-N concentration in ACS than PCS. The reason for this difference in nitrate leaching between ACS and PCS is uncertain. Field and laboratory studies have shown that significant amount of nitrate leaching can occur in N amended soil between 2 to 10 days after fertilization in the presence of sufficient precipitation (Zaman et al. 2008; Peng et al. 2015). Zaman et al. (2008) found that reducing nitrate-N accumulation during the early days after fertilization with the use of inhibitors will in the long run result in significant reduction of nitrate leaching. It is possible that the lack of manure incorporation in PCS allowed applied ammonium-N to persist longer in PCS which thereafter resulted in observed lower nitrate leaching in PCS than ACS as it was in the study of Karimi et al. (2017). The exact mechanism(s) for the reduced nitrate leaching in PCS have not been clearly enunciated. This study was conducted to compare the short term persistence of ammonium-N in ACS and PCS following liquid and solid pig manures applications as a possible mechanism for reduced nitrate leaching below the root zones of perennial forage grasses.

MATERIALS AND METHODS

Site Description

The study was conducted as part of the National Centre for Livestock and the Environment long term rotation at the University of Manitoba Ian Morrison Research station, Carman, Manitoba (49° 29' 64" N, 98° 02' 15" W and 239 m a.s.l). The experimental site was established in 2009 on Hibsini series which is classified as Orthic Black Chernozem soil in the Canadian soil classification system (Mills and Haluschak 1993) which correlates to Udic Boroll Mollisol in the U.S.A classification system and as *Chernozem* in WRB/FAO classification system (Agriculture and Agri-Food Canada 2013). Prior to site establishment, physical and chemical properties of the soil at 0 - 15 cm were determined (Table 1). Particle size analysis was determined by pipette method (Gee and Bauder 1986); soil pH was measured in a 1:2 soil:water suspension (Hendershot and Lalande 2008); organic matter was determined by the Walkley-Black acid digestion method (Walkley and Black, 1934); volumetric water content at field capacity was determined as described by Cassel and Nielsen (1986); soil available P concentration was determined using the Olsen method (Olsen and Sommers 1982); soil bulk density was determined as the ratio of oven dry weight of soil to the total volume of soil (Hao et al. 2008).

Experimental Design and Manure Application

The experimental design was a split-plot design with four replications. Each plot was 10 x 10 m. Main plots were cropping system and subplots were three manure treatments. Cropping system treatments were ACS and PCS, and manure treatments were nitrogen-based application rate of liquid pig manure (LPM); nitrogen-based application rate of solid pig manure (SPM) and check to which neither solid nor liquid pig manures was applied (CON). The ACS was seeded to a

canola (*Brassica napus* L.) - barley (*Hordeum vulgare* L.) rotation from 2009 to 2015 and the PCS was seeded to perennial forage grasses from 2009 to 2012. In spring 2013, the perennial forage grasses were ploughed down and seeded to annual crop (canola) and in fall 2013, the perennial forage grasses were reseeded and maintained until 2015. The perennial forage grasses seeded were a mixture of timothy grass (*Phleum pratense* L; var. Promesse) and orchard grass (*Dactylis glomerata* L; var. AC Nordic) at a seeding ratio of 68:32. The ACS was seeded to barley (var. Tradition) in 2014 and canola (hyb. Invigor L140P) in 2015.

In spring of each year, liquid pig manure was sourced from earthen manure storage of a commercial pig farm in Manitoba while solid pig manure was sourced from stockpiled pig manure with covered roof at Glenlea Research Station of the University of Manitoba, Manitoba. The ammonium-N concentrations and total N of the manures were determined (Table 2) and used to set manure application rates (Table 3) based on crop N requirement, residual nitrate in soil (0 - 60 cm), N content of the manure and assuming 25% ammonia volatilization losses of manure ammonia and 25% of the organic N of manures available to the crop in the year of application (MARC 2008; MAFRI 2007). Target yields of crops were 4,600 kg ha⁻¹, 2,200 kg ha⁻¹ and 7,400 kg ha⁻¹ for barley, canola and perennial forage grasses, respectively. The SPM was applied to the surface of the plots manually using a pitch fork and a rake. The LPM was metered out using 20 L jugs and manually added to the plots. After the application of both manures, the ACS plots were rototilled to incorporate the manures to a depth of approximately 10 cm before seeding in each year (Nikiema et al. 2016).

Soil Sampling and Analysis

In 2014, soil samples were collected 17 d before manure application and 4, 7, 11, 14, 18, 21, and 27 d after manure application at soil depths of 0 - 15 cm and 15 - 30 cm using a 1.8 cm internal diameter tube sampler (backsaver probe, Clements Associates Inc., IA, USA). Five random soil samples were collected and mixed to provide one composite sample for a plot. In 2015, the soil was sampled more frequently and not beyond 14 d as the 2014 data showed little persistence of ammonium-N beyond 14 d. Soil was therefore sampled 4 d before manure application and 2, 4, 7, 9, 11, and 14 d after manure application at soil depths of 0 - 15 cm and 15 - 30 cm. In 2015, a composite soil sample of seven sub-samples was taken randomly within each plot. Soil ammonium-N and nitrate-N were extracted (6 g field moist soil in 25 mL 2 M KCl) as described by Maynard et al. (2008) and analyzed colorimetrically using an AQ2 Discrete Analyzer (SEAL Analytical Inc., WI, USA). The ammonium-N and nitrate-N concentrations were expressed on a kg ha^{-1} basis.

Calculation

Persistence of ammonium-N ($\text{NH}_4^+_{(p)}$) was calculated as:

$$\% \text{NH}_4^+_{(p)} = [\text{NH}_4^+_{(t)} / \text{NH}_4^+_{(0)}] \times 100 \quad [1]$$

Where: $\text{NH}_4^+_{(t)}$ refers to amount of ammonium-N (kg ha^{-1}) in soil at time t where t is sampling day; $\text{NH}_4^+_{(0)}$ refers to amount of applied manure ammonium-N (kg ha^{-1}).

Kinetic Model of Nitrification

The quantity of ammonium-N (kg ha^{-1}) measured up to 14 d (ammonium-N on 18, 21, and 27 d were not included because of the very low ammonium-N on these days) in 2014 was used to generate apparent nitrification rate (K_n) for each cropping system assuming first order kinetics using PROC REG in SAS 9.4 (SAS Institute 2014). The K_n that was generated in 2014 was validated using the ammonium-N data obtained in 2015. The first order kinetic model is given as:

$$\ln \text{NH}_4^+_{(t)} = \ln \text{NH}_4^+_{(0)} - K_n t \quad [2]$$

Where: K_n is first order rate constant (apparent nitrification rate) and other parameters are as previously defined.

Statistical Analysis

Statistical analysis of the data was performed using PROC GLIMMIX for repeated measures in SAS 9.4 analysis software package (SAS Institute 2014) to test for significance effect of cropping system, manure treatment, sampling date (day) and their interactions on amount of soil ammonium-N and nitrate-N. Data were analyzed separately by depth (0 - 15 and 15 - 30 cm) and year (2014 and 2015). Means comparisons were performed using Tukey and treatment differences were considered significant at $P < 0.05$. Prior to PROC GLIMMIX analysis, soil ammonium-N and nitrate-N data was checked for assumption of normal distribution using PROC UNIVARIATE. Except for nitrate-N in 2014, the data did not conform to normal distribution and they were specified for lognormal distribution in the model. Cropping systems, day and manure treatments were fixed effects while block and its interactions with the fixed effects were random

effects. The covariance structure used in the model was compound symmetry in which the repeated factor (day) had unequal intervals. A PROC REG was used to test for significant difference between the generated K_n of the two cropping systems for each manure treatment (IDRE 2016). PROC REG was used to test the correlation between the observed and simulated ammonium-N for each manure treatment and to evaluate the model accuracy with the normalised root-mean-square error. Nash-Sutcliffe coefficient (E) was also used to access the accuracy of the model to simulate the observed ammonium-N in 2015 (Moriassi et al. 2007).

Nash-Sutcliffe coefficient equation was calculated as:

$$E = 1 - \frac{\sum_{i=1}^n (X_i^{obs} - X_i^{sim})^2}{\sum_{i=1}^n (X_i^{obs} - X_{mean})^2} \tag{3}$$

Where: X^{obs} is the observed ammonium-N in soil, X^{sim} is the simulated ammonium-N, X_{mean} is the mean of observed ammonium-N in soil.

RESULTS

Environmental Conditions

The period of sampling in this study was in spring when environmental factors such as temperature and moisture were not limiting for nitrification process. Air temperature ranged from 12 to 21 °C in 2014 and 13 to 21 °C in 2015 (Fig. 1). Highest precipitation was on 21 d in 2014 and on 5 d in 2015 (Fig. 1).

Concentration of Ammonium-N following Manure Application

In 2014, there were significant cropping system x day x manure treatment interactions on soil ammonium-N at 0 - 15 cm depth (Table 4). The quantity of ammonium-N measured in each cropping system depended upon manure treatment and the sampling day. In contrast, there were no significant cropping system x day x manure treatment interactions on soil ammonium-N at 0 - 15 cm depth in 2015 but the two-way interactions for cropping system x manure treatment and day x manure treatment were significant (Table 4). There was a significant difference between PCS and ACS in the concentration of ammonium-N at 0 - 15 cm depth at 7 d in LPM amended treatment only, in both years (Fig. 2 and 3). At 15 - 30 cm depth, there were no significant cropping system x day x manure treatment interactions in the amounts of ammonium-N in both years.

Expectedly, the amount of ammonium-N in all the manure treatment and cropping system at the first sampling date (before manure application) was low (less than 3 kg ha⁻¹ in 2014 and less than 5 kg ha⁻¹ in 2015) (Fig. 2 and 3). Following manure application in 2014, large amounts of ammonium-N were measured in all plots (including the CON treatments where no manure was added) by 4 d at 0 - 15 cm depth. The highest amount of ammonium-N was in the LPM amended treatment (50 kg ha⁻¹ in the PCS and 29 kg ha⁻¹ in the ACS; Fig. 2). In 2015, large amounts of ammonium-N were measured only in the LPM amended treatment (74 kg ha⁻¹ in PCS and 18 kg ha⁻¹ in ACS; Fig. 3) by 4 d at 0 - 15 cm. Ammonium-N was highest in the LPM amended treatment due to higher amounts of ammonium-N being added with LPM than with SPM whereas the least amount of ammonium-N was in CON treatment. LPM amended treatment received 93 - 95% of its available N in the ammonium-N form in both years whereas SPM amended treatments received 41 - 43% of its available N in ammonium-N form (Table 3). The

amount of ammonium-N at 15 - 30 cm depth was relatively small in all manure treatments, cropping systems and years (Fig. 2 and 3).

Concentration of Ammonium-N in LPM Amended Treatments

Ammonium-N in the LPM amended ACS and PCS reached its peak by 4 d at 0 - 15 cm depth in 2014 and 2015 but persisted until 7 d only in the PCS in both years (Fig. 2 and 3). Apparent ammonium-N (ammonium-N in manure amended soil minus that in control soil) was closer in magnitude to the ammonium applied in PCS than ACS by 4 d. At 7 d in both years, ammonium-N was significantly greater in LPM amended PCS than in ACS, an indication of a greater persistence of ammonium-N in PCS. In 2014, the persistence of ammonium-N was 77% and 14% in the PCS and ACS, respectively at 7 d. Despite the mature sward of perennial forage grasses in 2015 with a greater potential for N uptake, the persistence of ammonium-N in the LPM amended PCS was still greater than in ACS. Persistence of ammonium-N in 2015 was 46% and 8% in the PCS and ACS, respectively at 7 d. In 2014, ammonium-N at 15 - 30 cm depth interval was significantly greater in PCS than ACS at 7 d despite the limited mobility of ammonium-N from surface soil to subsoil (Fig. 2).

Concentration of Ammonium-N in SPM Amended Treatments

In the SPM amended treatment, there were no significant differences in ammonium-N between the ACS and PCS on any sampling day at either depth in 2014 or 2015. Amount of ammonium-N in SPM amended ACS and PCS was small throughout the sampling periods in both years. Unlike the LPM amended treatments that had higher ammonium-N in the first week after manure application, SPM amended treatment had low ammonium-N in the first week after application (Fig. 2 and 3). The pattern of ammonium-N in SPM amended treatments was similar to that in

the CON where no manure was added (Fig. 2 and 3). The persistence of ammonium-N at 7 d in SPM amended treatment was 45% for PCS and 27% for ACS in 2014. In 2015, persistence of ammonium-N at 7 d in SPM amended PCS was 17% while that of ACS was 55%.

Concentration of Nitrate-N following Manure Application

In 2014, there were significant cropping system x day x manure treatment interactions on nitrate-N measured at 0 - 15 cm and 15 - 30 cm depth intervals (Table 4). The differences in nitrate-N between the cropping systems depended on the manure treatment and day of sampling. In 2015, there were no significant cropping system x day x manure treatment interactions on nitrate-N at either 0 - 15 cm or 15 - 30 cm depth (Table 4). Nitrate-N was higher in ACS than PCS and significantly higher in LPM amended treatment than other manure treatment in 2015.

Concentration of Nitrate-N in LPM Amended Treatments

Following manure application in each year, there was an increase in nitrate-N of ACS and PCS at 0 - 15 cm depth but not all of the increase could be attributed to nitrification from the added ammonium-N since there was also an increase in nitrate-N of CON treatment where no manure was added (Fig. 4 and 5). Moist soil condition and increased temperature after manure application allowed nitrification to proceed in both cropping systems. In 2014, nitrate-N in the LPM amended soil was significantly greater in ACS than PCS at 7 d despite the slightly higher initial nitrate-N in PCS prior to manure application (Fig. 4). The nitrate-N of the LPM amended ACS increased by 31% between 4 and 7 d but decreased by 8% in the PCS. The significantly greater nitrate-N in PCS than ACS at 14 d was due to the sharp decline in nitrate-N in the ACS but was not the case in the PCS. This decline in the nitrate-N of the ACS at 0 - 15 cm depth was due to downward nitrate movement as a result of rainfall and resulted in a significantly greater

nitrate-N accumulation in ACS than PCS on 14 d at the 15 - 30 cm depth (Fig. 4). In 2015, nitrate-N at 0 - 15 cm depth was greater in ACS than PCS up to 14 d but was only significant on three of the five sampling days (Fig. 5). Although the difference in nitrate-N at 0 - 15 cm between ACS and PCS was not significant on 7 d in 2015 as it was in 2014, nitrate-N was significantly greater in ACS than PCS at 9 d and 14 d. At 15 - 30 cm depth interval, nitrate-N was significantly greater in ACS than PCS from 9 - 14 d in 2015.

Concentration of Nitrate-N in SPM Amended Treatments

In 2014, nitrate-N in SPM amended treatments was greater in PCS than ACS at 0 - 15 cm depth due to the significantly greater initial nitrate-N (before manure application) (Fig. 4). In 2015, nitrate-N at 0 - 15 cm depth was greater in ACS than PCS from the time of manure application up to 14 d with significant differences on three of the five sampling days (Fig. 5). At 15 - 30 cm depth in 2014, nitrate-N of SPM amended PCS was significantly greater than that in ACS at five of the eight sampling times (Fig. 4) mainly due to the significantly greater initial nitrate-N. However, the percentage increase in nitrate-N (relative to the initial measurement) was greater in the ACS than in the PCS until 21 d (Fig. 4). In 2015, nitrate-N between the cropping systems at 15 - 30 cm depth was not significantly different from the time of manure application until 7 d when nitrate-N of ACS became significantly greater than that in PCS.

Nitrogen Transformation following Manure Application

The first order rate constant for K_n was 0.24 d^{-1} in LPM amended ACS and PCS; and 0.21 d^{-1} for SPM amended ACS and PCS (Table 5). The K_n were not statistically different between the cropping systems for each manure treatment ($P = 0.9115$ for LPM and $P = 0.9402$ for SPM). In both cropping systems, the normalized root-mean-square error showed that the error of

predictability of K_n generated by the model was less than 25 and 35% in LPM and SPM, respectively (Table 5).

The formulated kinetic model fit the ammonium-N data of the LPM amended treatment in 2015 as indicated by the R^2 (Table 6). There was a significant correlation between simulated and observed ammonium-N in the LPM amended ACS and PCS in 2015 with a better simulation in ACS than in PCS (Table 6 and fig. 6). In contrast, the model did not fit the ammonium-N data in the SPM amended PCS and ACS as there was no significant correlation between the simulated and observed ammonium-N (Table 6 and fig. 6). The normalized root-mean-square error showed that the error of predictability of K_n to simulate ammonium-N in 2015 was lower in LPM amended ACS and PCS than SPM amended ACS and PCS (Table 6). This was supported by the positive value of Nash-Sutcliffe coefficient in LPM amended ACS and PCS (Table 6). The model fit better in LPM amended ACS than PCS (Nash-Sutcliffe coefficient of 0.79 versus 0.47)

DISCUSSION

Concentration of Ammonium-N following Manure Application

The magnitude of ammonium-N measured at 0 - 15 cm depth in SPM and LPM amended treatments at 4 d was similar to that measured by Ige et al. (2015) based on the relative quantities of ammonium-N that were applied. The initial increase in ammonium-N after manure application followed by a decline was similar to the results reported by Calderón et al. (2005) and Ige et al. (2015) who showed that ammonium-N reached its peak following manure application and declined gradually within a week after manure application. The greater persistence of ammonium-N in the LPM amended PCS signified a delay in the nitrification process perhaps due to a lack of manure incorporation into the soil. This persistence is similar to the action of

nitrification inhibitor such as nitrapyrin that delays the microbial oxidation of ammonium to nitrite after N application (Zerulla et al. 2001). It is possible that the lack of incorporation of manure in the PCS created zones of high ammonium concentration that inhibited activities of nitrifying organisms. Koper et al. (2010) reported that significant nitrification inhibition may occur in soil after N application due to the toxic zone created by high ammonium concentration for the oxidizing organisms. The reduced persistence of ammonium-N in ACS may be due to higher dilution effect and greater contact of manure with the soil leading to higher microbial activities. The amount of ammonium-N in the SPM amended treatments was not sufficient to cause ammonium toxicity to soil microorganisms. Although soil pH has significant effect on nitrification (Ste-Marie and Pare 1999), the presence of similar pH in both cropping systems (6.6 in ACS and 6.4 in PCS) after five years of continuous manure application on these plots (Adesanya 2015) made the soil pH a less likely factor in the persistent ammonium-N in PCS. Similarly, the lack of significant difference in soil moisture content between PCS and ACS at this period of persistent ammonium-N (data not shown) limits the effect of moisture on the differences in amount of ammonium-N observed. Low ammonium-N measured from 11 to 21 d in 2014 in this study was similar to results from other studies that showed small and relative stable ammonium-N two weeks after manure application (Calderón et al. 2005; Li and Li 2014). The low ammonium-N at the 15 - 30 cm was due to the limited mobility of ammonium in soil and its adsorption to the negatively charged soil surfaces at the 0 - 15 cm (Nieder et al. 2011; Scherer et al. 2014).

Concentration of Nitrate-N following Manure Application

The distribution of nitrate-N in both cropping system with time suggests that the lower accumulation of nitrate-N in the PCS in both years was due to a delay in the nitrification process

and the possibility of an immediate uptake of nitrate-N upon its formation. Smaller increase in amounts of nitrate-N in the LPM amended PCS was consistent with the persistence of ammonium-N until 7 d. Conversely, the greater increase in amounts of nitrate-N in the ACS were consistent with the lack of ammonium-N persistence as indicated by the small amounts of ammonium-N at 7 d. Studies have shown that nitrate-N accumulation can be minimized by allowing N to stay longer in the ammonium form (Zerulla et al. 2001) thereby reducing the potential for nitrate leaching. Guiraud and Marol (1992) reported that the amount of nitrate-N in the soil during the period of ammonium-N persistence due to the application of nitrification inhibitor was lower than in the soil where there was no nitrification inhibitor. In another study, van Es et al. (2006) attributed the higher accumulation of nitrate-N in an ACS to the incorporation of manure. Li et al. (2015) reported that the lack of tillage might make applied N to be retained longer in ammonium form thereby reducing nitrate accumulation in the soil. Incorporation of manure in the ACS would make the substrate (ammonium) more easily accessible to the nitrifying organism and improve aeration thereby increasing the formation of nitrate. Nevertheless, the infiltration of LPM into the soil might compensate for the lack of incorporation especially on this kind of soil (loamy sand) and also the presence of significantly lower bulk density in PCS than ACS at 0 - 10 cm before manure application on these plots (Adesanya et al. 2016), might make the smaller amount of nitrate-N in the PCS not to be entirely due to a lack of incorporation. The significantly greater nitrate-N accumulation in CON treatments of ACS than PCS suggests that incorporation alone might not completely account for the greater nitrate-N accumulation in ACS. The observed greater increase in nitrate-N at 15 - 30 cm of the ACS between 7 and 11 d might be due to the occurrence of 38.8 mm of rainfall which moved the nitrate-N formed at the soil surface; whereas this rainfall event did not result in a

rapid increase in nitrate-N at 15 - 30 cm of the PCS because of its lower nitrate-N accumulation. Thus, a higher nitrate-N accumulation at this early period following manure application might in the long run result in a significant nitrate leaching (Zaman et al. 2008). The differences in growth stage between the crops might have led to the greater percentage increase of nitrate-N at 15 - 30 cm depth of ACS than PCS. Lower nitrate-N in PCS than ACS in 2015 might be due to uptake of nitrate-N in PCS since the perennial forage grasses were well established at this period of the growing season. This was because the annual crops were at the germination stage with little N uptake unlike the perennial forage grasses that were at vegetative stage and required greater amount of N (Delgado and Follett 2010). This greater percentage increase of nitrate-N in ACS compared to PCS at this early time of the growing season (spring) is an indication of a greater potential for nitrate leaching in the ACS than PCS in case of any rainfall or irrigation event as ACS have been reported to leach a greater amount of nitrate-N in soil (Randall and Mulla 2001; Dinnes et al. 2002).

Nitrogen Transformation following Manure Application

The K_n obtained in this study were smaller than those obtained by both Koper et al. (2010) and Habteselassie et al. (2006) who used inorganic fertilizers and compost, but greater than those obtained by Bolado-rodríguez et al. (2010) using pig slurry. The study by Koper et al. (2010) reported that K_n is affected by source of N and ammonium oxidizing organisms in the soil. The K_n in this study can be used to predict transformation of ammonium-N in soil amended with LPM but not with SPM. Positive Nash-Sutcliffe coefficient in LPM amended ACS and PCS showed that the model is a better predictor than the observed mean whereas the negative value of Nash-Sutcliffe coefficient showed that the observed mean is a better predictor of the model (Moriasi et al. 2007). The lack of correlation between measured and simulated ammonium-N in

SPM amended treatment and the negative Nash-Sutcliffe coefficient might be due to the small amount of ammonium-N in SPM and its rapid immobilization.

CONCLUSION

Ammonium-N in LPM amended ACS and PCS peaked at 4 d in both years of study and persisted until 7 d in PCS, but not beyond 4 d in ACS. Low concentrations of ammonium-N were measured in SPM amended ACS and PCS on 4 and 7 d in both years. There was lower accumulation of nitrate-N in the PCS than ACS at both depth intervals in both years. The first order rate constants for K_n in ACS and PCS were similar for each manure treatment in 2014 and the K_n generated in 2014 simulated ammonium-N dynamics in 2015 for LPM amended treatments only. Nash-Sutcliffe coefficient showed that the model is a better predictor than the observed mean in LPM amended treatment only. Persistence of ammonium-N in LPM amended PCS may be as a result of high ammonium-N concentration created by the lack of manure incorporation into the soil. The persistence of ammonium-N in the LPM amended PCS than ACS coupled with lower accumulation of nitrate-N in PCS may partly account for lower nitrate leaching that has been reported for perennial forage grasses.

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LIST OF ABBREVIATIONS

LPM is N-based application rate of liquid pig manure; SPM is N-based application rate of solid pig manure; CON is a check with no manure added; ACS is annual cropping system; PCS is perennial cropping system.

For Review Only

Table 1. Characteristics of the soil at Carman

Soil Properties	Carman
Soil pH	5.8
Organic matter (g kg ⁻¹)	65.0
VWC ^a (m m ⁻³)	33.0
Plant available P (mg kg ⁻¹)	20
Bulk density (Mg m ⁻³)	1.2
Soil type	Loamy sand
Sand content (g kg ⁻¹)	870.0
Silt content (g kg ⁻¹)	50.0
Clay content (g kg ⁻¹)	80.0

^aVolumetric water content at field capacity

Table 2. Pertinent properties of the liquid (LPM) and solid (SPM) pig manures applied to the plots in 2014 and 2015.

Year	Manure	Moisture (kg L ⁻¹ or kg kg ⁻¹)	Total N(mg L ⁻¹ or mg kg ⁻¹).....	NH ₄ ⁺ -N	Available N
2014	LPM	0.99	1600	1351	1086
	SPM	0.77	7100	1350	2440
2015	LPM	0.99	2500	2154	1694
	SPM	0.84	5800	1177	2014

Note: Moisture content and N concentrations are expressed in kg L⁻¹ and mg L⁻¹, respectively for LPM and kg kg⁻¹ and mg kg⁻¹, respectively for SPM.

Table 3. Manure type, residual soil nitrate-N, manure application rate, available organic N and ammonium-N fractions applied, available N applied and Plant available N in 2014 and 2015.

Year	Crops	Manure	Residual soil NO ₃ ⁻ -N (kg ha ⁻¹)	Manure rates (L or tonne ha ⁻¹)	Avail. ^a Org. N	NH ₄ ⁺ -N applied (kg ha ⁻¹).....	Avail. N applied	Plant avail. N
2014	ACS ^b (Barley)	LPM ^d	50.4	46 470.0	3.4	47.1	50.5	100.9
		SPM ^e	52.0	20.5	28.9	20.5	49.4	101.4
		CON ^f	17.6	0	NA	NA	NA	NA
	PCS ^c	LPM	87.4	48 260.0	3.5	48.9	52.4	139.8
		SPM	101.9	16.0	22.8	16.2	39.0	140.9
		CON	27.4	0	NA	NA	NA	NA
2015	ACS (Canola)	LPM	83.2	33 610.0	2.7	54.3	57.0	140.2
		SPM	109.2	15.8	18.2	13.9	32.1	141.3
		CON	38.3	0	NA	NA	NA	NA
	PCS	LPM	45.9	55 562.0	4.4	89.8	94.2	140.1
		SPM	84.3	27.0	31.2	23.8	55.0	139.3
		CON	16.4	0	NA	NA	NA	NA

Note: Manure rates are expressed in L ha⁻¹ for LPM and tonne ha⁻¹ for SPM.

^aAvail. is available;

^bACS is annual cropping system.

^cPCS is perennial cropping system.

^dLPM is N-based application rate of liquid pig manure.

^eSPM is N-based application rate of solid pig manure.

^fCON is a check with no manure added.

^gNA is not applicable.

Table 4. Effect of cropping systems and manure treatments on ammonium-N and nitrate-N with time in 2014 and 2015 at 0 - 15 cm and 15 - 30 cm depth intervals.

Model effect	Df	0 - 15 cm		15 - 30 cm	
		NH ₄ ⁺ -N	NO ₃ ⁻ -N	NH ₄ ⁺ -N	NO ₃ ⁻ -N
2014		P values.....			
Cropping system (CS)	1	0.2483	0.1272	0.4578	0.1633
Manure treatment (MT)	2	0.2232	0.0003	0.0182	<.0001
Day	7	<.0001	<.0001	0.0044	<.0001
CS x MT	2	0.2079	0.0185	0.2040	0.0249
CS x day	7	0.1562	0.2831	0.2266	<.0001
Day x MT	14	0.0008	<.0001	0.0023	0.0003
CS x day x MT	14	0.0399	0.0069	0.3584	0.0161
2015					
CS	1	0.0572	<.0001	0.0226	0.0517
MT	2	0.0012	<.0001	0.1840	<.0001
Day	6	0.0004	<.0001	0.0021	0.3137
CS x MT	2	0.0280	0.0014	0.1676	0.4689
CS x day	6	0.4382	<.0001	0.3641	<.0001
Day x MT	12	<.0001	<.0001	0.3784	0.0665
CS x day x MT	12	0.1278	0.4140	0.9438	0.0937

Note: P values are significant at P < 0.05 Tukey means comparison.

Table 5. Kinetics of apparent nitrification rate (K_n) in manure treatments and cropping systems at 0 - 30 cm in 2014

Manure	Cropping system	Model fitting		
		R^2	K_n (d^{-1})	NRMSE ^a
LPM ^b	ACS ^d	0.89	0.24	0.19
	PCS ^e	0.79	0.24	0.23
SPM ^c	ACS	0.84	0.21	0.22
	PCS	0.77	0.21	0.31

^aNRMSE is normalized root-mean-square error.

^bLPM is N-based application rate of liquid pig manure.

^cSPM is N-based application rate of solid pig manure.

^dACS is annual cropping system.

^ePCS is perennial cropping system.

Table 6. Comparison between observed and simulated ammonium-N in each cropping system and manure treatment at 0 - 30 cm in 2015.

Manure	Cropping system	R ²	Model Validation		E ^b
			P values	NRMSE ^a	
LPM ^c	ACS ^e	0.84	0.0036	0.47	0.79
	PCS ^f	0.76	0.0103	0.36	0.47
SPM ^d	ACS	0.05	0.6198	1.43	- 0.51
	PCS	0.05	0.6393	1.21	- 0.22

Note: P values are significant at $P < 0.05$ Tukey means comparison.

^aNRMSE is normalized root-mean-square error.

^bE is Nash-Sutcliffe coefficient.

^cLPM is N-based application rate of liquid pig manure.

^dSPM is N-based application rate of solid pig manure.

^eACS is annual cropping system.

^fPCS is perennial cropping system.

Figure Captions

Fig. 1. Daily mean air temperature and precipitation at Carman in 2014 and 2015 (Environment Canada).

Fig. 2. Effect of cropping systems and manure treatments on ammonium-N at 0 - 15 and 15 - 30 cm depths in 2014. Error bars are standard error of the means.

*Ammonium-N was significantly different between ACS and PCS at $P < 0.05$ Tukey means comparison on this day. LPM is N-based application rate of liquid pig manure; SPM is N-based application rate of solid pig manure; CON is a check with no manure added; ACS is annual cropping system; PCS is perennial cropping system.

Fig. 3. Effect of cropping systems and manure treatments on ammonium-N at 0 - 15 and 15 - 30 cm depths in 2015. Error bars are standard error of the means.

* Ammonium-N was significantly different between ACS and PCS at $P < 0.05$ Tukey means comparison on this day.

LPM is N-based application rate of liquid pig manure; SPM is N-based application rate of solid pig manure; CON is a check with no manure added; ACS is annual cropping system; PCS is perennial cropping system.

Fig. 4. Effect of cropping systems and manure treatments on nitrate-N at 0 - 15 and 15 - 30 cm depths in 2014. Error bars are standard error of the means.

*Nitrate-N was significantly different between ACS and PCS at $P < 0.05$ Tukey means comparison on these days.

LPM is N-based application rate of liquid pig manure; SPM is N-based application rate of solid pig manure; CON is a check with no manure added; ACS is annual cropping system; PCS is perennial cropping system.

Fig. 5. Effect of cropping systems and manure treatments on nitrate-N at 0 - 15 and 15 -30 cm depths in 2015. Error bars are standard error of the means.

*Nitrate-N was significantly different between ACS and PCS at $P < 0.05$ Tukey means comparison on these days.

LPM is N-based application rate of liquid pig manure; SPM is N-based application rate of solid pig manure; CON is a check with no manure added; ACS is annual cropping system; PCS is perennial cropping system.

Fig. 6. Validation of nitrification kinetics model in 2015 using the ammonium-N data (0 - 30 cm) obtained in 2014.

LPM is N-based application rate of liquid pig manure; SPM is N-based application rate of solid pig manure; ACS is annual cropping system; PCS is perennial cropping system.

Fig. 1

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