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ORIGINAL ARTICLE

Nitrogen- or phosphorus-based pig manure application rates affect soil test phosphorus and phosphorus loss risk

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Abstract Pig manure is an effective source of plant nutrients that must be properly managed to prevent these nutrients from reaching surface and ground water. We conducted a 3-year study in southern Manitoba to investigate how the choice of cropping system and manure management practices affect soil test phosphorus (STP) concentration and loss of phosphorus (P) to groundwater. The experiment had a split-plot design with two cropping systems (annual and perennial) as main plots, and five nutrient management treatments as subplots: N-based liquid pig manure, P-based liquid pig manure, N-based solid pig manure, P-based solid pig manure and an unfertilized control. We did not measure an appreciable increase in STP concentration below the 0.15 m depth. However, manure application at an N-based rate resulted in increased STP concentration in the 0–0.15 m depth interval. After 3-year, STP concentration in the N-based treatments (48 and 43 mg Olsen P kg^{-1} for solid and liquid respectively) were significantly greater than for the P-based treatments (26 and 17 mg Olsen P kg^{-1} for solid and liquid respectively). The mass of P in the leachate was small, ranging from a low of 1 g P ha^{-1} in 2009 to a high of 100 g P ha^{-1} in 2011. Both P- and N-based manure application rates produced no apparent risk of P leaching at our site, but the N-based manure application rate increased STP concentration in the surface soil, which could lead to the loss of P in surface runoff.

Keywords Phosphorus · Pig · Manure · Leaching · STP

Introduction

Pig manure is widely applied as an amendment to agricultural lands (Flaten et al. 2003) and provides nutrients and organic matter to the soil (Ro et al. 2016), so it can be an excellent resource for agriculture. Excess applications of livestock manure, however, can result in the loss of phosphorus (P) from agricultural land and consequent degradation of groundwater, streams and lakes (Allen et al. 2006). At very low concentrations, P can cause excessive plant growth and algal blooms. Oxygen consumption by plants and algae can deplete oxygen in water resulting in odor and fish kill (Worsfold et al. 2016; Zhang et al. 2015).

Large algal blooms have occurred in Lake Winnipeg as a result of P driven eutrophication (Flaten

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et al. 2003). The main cause of this process appears to be the excess nutrient load of the Red River and other tributaries in the upstream regions (Alberta, Saskatchewan, Ontario and USA), from rural and urban areas alike. To address this issue, the Manitoba Government has proposed new P regulations affecting mainly agriculture and livestock production. This regulation stipulates that farmers add their manure based on crop P removal as the soil P level reaches a certain threshold (60 mg Olsen P kg^{-1}).

Earlier studies on P movement in soil focused on changes in soil P concentration with depth which has resulted in the general assumption that very little P leaching occur because of the high P-fixation capacity in many mineral soils (Toor and Sims 2016). Nevertheless, many studies have conclusively established that P leaching can be a major pathway of P loss from agricultural soils and eutrophication of downstream water bodies (Kleinman et al. 2015; King et al. 2015; Toor and Sims 2015; Zhang et al. 2015; van Es et al. 2004). Phosphorus leaching is a slow process and can continue for many years before becoming an environmental threat, especially in soils with low P sorption capacities (e.g., sandy soils and soils with high organic matter content), high soil P levels (e.g., soil with long-term P application history) and artificial drainage (e.g., tiles and ditches; King et al. 2015; Nelson et al. 2005). Despite these widespread efforts, many of the agricultural practices controlling P leaching remain elusive.

Manure is typically applied to meet the N requirements of the subsequent crop (Olson et al. 2010). Repeated, annual applications of manure, based on N requirements of the crop often result in an over-application of manure P and a build-up of soil test P (STP) concentration (Pautler and Sims 2000; Olson et al. 2010). As STP concentration increases, the concentration of P in runoff also increases (Sharpley et al. 2009). However, annual applications of manure to meet the annual rate of crop P removal do not usually supply adequate N for optimum crop yields. Therefore, on high P soils it is recommended that manure be applied intermittently, based on multi-year crop P removal, with additional N fertilizer being applied between manure applications, to meet the N needs of the crop on an annual basis (Miller et al. 2011). Toth et al. (2006) showed that application of manure at N-based rates versus P-based rates (where ammonium sulfate fertilizer was used to meet the N requirement of crop) had similar magnitudes of P leaching losses from three perennial crops including alfalfa, corn silage, and orchard grass. However, the N-based manure resulted in greater STP values in the surface 0.05-m which has implications for increased risk of P loss in runoff. Kumaragamage et al. (2009) studied P runoff and leaching losses from different sources of solid cattle manure, liquid pig manure and monoammonium phosphate (MAP) in sand and clay loam soils. Their results showed that the proportion of P in liquid pig manure that was susceptible to runoff and leaching losses was generally greater than that in solid cattle manure, but less than in MAP.

Coppi (2012) measured P leaching following N-based pig manure application to south-eastern Manitoba grasslands. The author reported that subsurface movement of P was not environmentally significant during 6-year of continuous manure application compared to the non-manured control plots. It is clear from the literature that STP concentration and leaching P loss increases with higher rates of P addition. However, the literature that compares the changes in STP concentration build-up and P leaching loss concurrently in annual and perennial cropping systems that are treated with manure is scant. The objectives of this study were to determine the influence of cropping system (annual vs. perennial); nutrient management system (N- vs. P-based manure applications); and the type of pig manure (liquid vs. solid) on STP concentration and the loss of P below the root zone using a field core lysimeter.

Materials and methods

Site characteristics

Descriptions of the study area, experimental design, sampling protocols, and materials and methods were given by Karimi et al. (2017), and therefore only the salient information will be repeated in this paper. The study was carried out at the National Centre for Livestock and the Environment (NCLE), University of Manitoba Field Research Station, Carman, Manitoba between 2009 and 2011. The site was located on the Hibsin soil series with coarse loamy soil underlain by clayey deposits. These soils are moderately well-drained.

In the fall of 2006, the experimental site was seeded to a mixture of 50% alfalfa (*Medicago sativa* L.), 34% Timothy grass (*Phleum pratense* L.) and 16% Orchard grass (*Dactylis glomerata* L.). This was maintained with no added input until the spring of 2009 when the study was initiated. In the spring of 2009, the alfalfa was killed on the 'perennial' plots by spraying with 0.84 L ha^{-1} clopyralid; 3,6-Dichloropyridine-2-carboxylic acid (Lontrel) and 0.98 L ha^{-1} of 2-methyl-4-chlorophenoxyacetic acid (MCPA) herbicides, leaving a mixture of timothy ($\sim$ 68%) and orchard grass ($\sim$ 32%). The 'annual' plots were treated with the 5.5 L ha^{-1} of glyphosate; *N*-(phosphonomethyl) glycine, (Roundup) herbicide and ploughed into the soil.

Experimental design

The experiment had a split-plot design with two cropping systems (annual and perennial) as main plots, and five nutrient management treatments including Liquid-N (annual N based liquid pig manure to meet the crop N requirement), Liquid-P (once every 5-year P based liquid pig manure to match crop P removal), Solid-N (annual N based solid pig manure to meet the crop N requirement), Solid-P (once every 5-year P based solid pig manure to match crop P removal) and control that received no manure or fertilizer during the 3-year of study as subplots (10 m × 10 m) with four replications. The total number of plots within the field was: 5 treatments × 4 replicates × 2 cropping systems = 40 plots. There was a buffer of 5-m between the replicates and a buffer of 2-m between the subplots. A field core lysimeter was installed inside the bottom corner of each plot so that water movement and nutrient leaching could be measured directly. In this study, the lysimeters received the same nutrient treatments as the surrounding plot, and the incorporation of nutrients and seeding were carried out manually within the lysimeters. Each lysimeter included three main parts: the main column, the schedule 80 PVC pipe with an internal diameter of 0.54 and 1.06 m in length, representing root zone extension of annual crops; a circular perforated plate and a collection bottom cap. To reduce the disturbance of soil during installation a custom made hydraulic press was used to push down the main column of the lysimeter to a depth of 1 m. The main column was then pulled out of the soil and turned upside down. Geotextile fabric was placed on the soil to separate the soil from the perforated plate and collection basin. The perforated plates, collection caps and extraction pipes were then installed on the main columns. Details of lysimeters design and installation have been previously provided (Nikiema et al. 2013; Karimi et al. 2017). The annual crop was canola (*Brassica napus* L. '*Argentine*' *Conventional and Liberty Link tolerant*) in 2009; barley (*Hordeum vulgare* L. '*Tradition*') in 2010 and canola in 2011. For the perennial, timothy/orchard grass was maintained in all 3 years.

Manure and urea application and seeding dates

Liquid manure was manually broadcasted to the N- and P-based plots of both annual and perennial crops on 2 and 3, while solid pig manure was manually broadcasted to these plots on 11 and 12 June in 2009. The annual plots were rototilled (0.10 m depth) on 11 June to incorporate the killed alfalfa/grass sod. All annual plots were rototilled for the second time on 15 June to incorporate the manure and were then seeded to canola. Manures were not incorporated on the perennial plots as no tillage took place on these plots during the 3-year of study. Pig manures (solid and liquid) for N-based treatments and urea for P-based treatments were applied on 15, 16 and 17 June in 2010 and on 16 and 17 June in 2011 to the appropriate plots and incorporation and seeding were carried out on the same day in the annual plots.

Manure and urea application rates

To simplify the calculations of specific-targeted manure application rates, Manitoba Agriculture, Food and Rural Development produced a Manure Application Rate Calculator (MARC) as a provincial manure management planning software package (Manitoba Agriculture, Food and Rural Initiatives (MAFRI) 2007). The MARC software package uses manure nutrient analysis, crop requirements, nutrient availability and estimated nutrient losses to determine appropriate manure application rates (Table 1). In 2009, manure application rates were based on the N requirements of the crop using the residual soil nitrate–N for the entire experimental area and target yields for canola and grass. The killed alfalfa sod was credited with supplying 60.5 kg N ha^{-1} (Manure Application Rate Calculator (MARC) 2008). The P-based rates were applied to provide the replacement

Table 1 Analysis of manure as applied to field plots

Year	Solid manure						Liquid manure					
	Total P kg tonne^{-1}	Total N	NH_4^+-N	Org. N[a]	Avail. N[b]	Moisture %	Total P kg 1000 L^{-1}	Total N	NH_4^+-N	Org. N	Avail. N	Moisture %
2009	3.6	3.1	1.7	1.3	1.6	70	0.9	3.8	2.2	1.6	2.0	93
2010	n/a[c]	5.3	1.4	3.9	2.1	70	2.2	5.0	3.0	2.0	2.8	84
2011	3.8	6.5	0.4	6.2	1.8	78	0.7	2.7	2.1	0.6	1.7	98

[a] Org. N stands for organic nitrogen

[b] Avail. N stands for available nitrogen, calculated on the assumption that 25% of organic N is mineralized and 25% of ammonium-N is lost to volatilization

$$\text{Total available N} = \text{Ammonium N} \times (100\% - \%\,\text{Volatilization loss}) + 25\%\,\text{Organic N}$$

[c] The extracted samples for P were lost

for harvested export of P during a 5-year period (approximating typical farm rates). As such, no additional N was required (for the P-based treatments) in the year of application based on the quantity of manure that was added and the available N of that manure. Multi-year P-based manure application rates do not typically require adjustment for P availability since they have already been inflated to account for several years of P removal (Fraser and Flaten 2014).

In 2010 and 2011, manure was applied to the N-based treatments only. The N requirements on the P-based treatments were supplied by urea (Table 2). In 2010, a wet spring caused delay in acquiring manure from producers which did not allow for sufficient time to analyze the manure prior to field application. As such, liquid manure application rates were based on the Nova meter estimate of ammonium-N and standard reference values for organic N in liquid manure from a commercial pig barn in Manitoba. Actual liquid manure N application rates were back-calculated (Table 2) using manure nutrient analyses results (Table 1) from samples collected at the time of application.

Field and laboratory procedures

Manure sampling and nutrient analysis

Manure samples were collected before and/or during application to calculate the actual rates of nutrients applied. Pre-application solid manure samples were collected by digging into the pile and taking a minimum of 10 sub-samples from several locations. Representative liquid manure samples collected from agitated lagoon. Manure samples were analyzed for total N, ammonium N, organic N, and total P and dry matter. Total N and P in manure were determined using the wet oxidation method of Akinremi et al. (2003). At least three subsamples of each manure type were analyzed. Total N of the sample digest was then determined by the automated phenate colorimetric method (Maynard and Kalra 1993) using a Technicon Autoanalyzer. Total P in the sample digest was also measured colorimetrically but by the ascorbic acid-molybdate method (Murphy and Riley 1962). The inorganic ammonium and nitrate-N content in manure was determined by extracting fresh manure with 2 M KCl (Peters et al. 2003). This was followed by analysis using the automated cadmium reduction method and the automated phenate colorimetric method (Maynard and Kalra 1993) using a Technicon Autoanalyzer for nitrate and ammonium, respectively. Organic-N was estimated as the difference between the total-N and ammonium-N. Dry matter was determined by drying five 10 g sub-samples of manure at 70 °C for 24 h or until no further loss of mass was observed.

Soil sampling and nutrient analysis

Soil samples were collected in the spring (before the manure application), mid-season and at harvest during the 2009, 2010 and 2011 growing seasons. Soil was sampled at six depth intervals of 0–0.15, 0.15–0.30, 0.30–0.45, 0.45–0.60, 0.60–0.90 and 0.90–1.20 m for

Table 2 Application rates of manure and urea N and manure P to annual and perennial treatments in 2009, 2010 and 2011

Rotation (target yield)	Treatment[a]	Avail manure N applied (kg ha^{-1})	Urea N applied (kg ha^{-1})	Manure P applied (kg ha^{-1})
2009				
Annual canola[b] (1960 kg ha^{-1})	Liquid-N	58	0	25
	Liquid-P	58	0	25
	Solid-N	37	0	82
	Solid-P	37	0	82
	Control	0	0	0
Perennial grass (6700 kg ha^{-1})	Liquid-N	59	0	29
	Liquid-P	59	0	29
	Solid-N	37	0	90
	Solid-P	37	0	90
	Control	0	0	0
2010				
Annual barley (n/a)[c]	Liquid-N	219	0	172
	Liquid-P	0	134	0
	Solid-N	124	0	n/a
	Solid-P	0	134	0
	Control	0	0	0
Perennial grass (6700 kg ha^{-1})	Liquid-N	202	0	178
	Liquid-P	0	123	0
	Solid-N	76	0	n/a
	Solid-P	0	123	0
	Control	0	0	0
2011				
Annual canola (2356 kg ha^{-1})	Liquid-N	54	0	18
	Liquid-P	0	126	0
	Solid-N	111	0	232
	Solid-P	0	112	0
	Control	0	0	0
Perennial grass (6700 kg ha^{-1})	Liquid-N	94	0	35
	Liquid-P	0	136	0
	Solid-N	132	0	282
	Solid-P	0	135	0
	Control	0	0	0

[a] Manure was applied to both N- and P-based plots in 2009 while it was only applied to the N-based plots in 2010 and 2011

[b] Herbicide-tolerant: Conventional (2009) and Liberty Link tolerant (2011)

[c] Due to the late seeding date, barley was planted instead of wheat while target yields was for wheat

spring and harvest using a 0.04 m slotted hydraulic probe (Giddings, #15-TS/Model GSRTS, CO). The mid-season sampling event was similarly undertaken, except with a 0.05 m Dutch auger and the lower 0.90–1.20 m depth increment was omitted. To reduce variation within the plot, two soil core samples were taken from each plot and composited.

We extracted Olsen-P by shaking 1.0 g field moist soil with 20 mL of 0.5 M $NaHCO_3$ with 0.25 g of P-free charcoal for 30 min (Olsen et al. 1954) and filtering the extract through Whatman no. 40 filter paper. Molybdate-reactive P in the extract was determined using the colorimetric method of Murphy and Riley (1962). Absorbance was measured at 882 nm wavelength using an Ultrospec 3100 UV visible spectrophotometer (Biochrom Ltd., Cambridge, UK).

Plant sampling and nutrient analysis

Plant samples were collected in each year at mid-season and at harvest. In each plot, biomass samples were taken in four randomly-selected areas using a 0.25 m^2 quadrat for a total area of 1 m^2. In 2011, 2.0 m^2 areas were sampled to reduce the variability in yield data. The plant material was put in cloth bags and hung in a drying room at room temperature (25 °C) for 30 days after which the seed was threshed and the seed, straw and grass weights determined. The mid-season and harvest biomass were sub-sampled and finely ground with a mini-ball mill for total P using the wet oxidation technique of Akinremi et al. (2003). The 2011 plant biomass samples were analyzed for P by Agvise Laboratories, Northwood, North Dakota in 2013 using a nitric acid/hydrogen peroxide digestion method followed by P determination using a Perkin Elmer 5400 ICP (Jones 2001).

Leachate sampling and nutrient analysis

Leachate was collected from bottom cap of the lysimeters three to five times, depending on the amount of precipitation annually (i.e., on 25 June, 7 August, 28 September and 17 November in 2009; on 4 June, 14 July, 24 August, 30 September and 2 November in 2010; on 16 May, 9 June, 6 July and 11 October in 2011). The total volume of leachate from each lysimeter was recorded and the total reactive P in unfiltered leachate samples was determined using the colorimetric method of Murphy and Riley (1962). Annual flux of P was determined by multiplying concentration of P (mg L^{-1}) in the leachate by the total leachate volume (L) for each sampling time and summed for 1-year. The flow-weighted mean concentration of P (FWMCP) was calculated by dividing the total flux of P by the corresponding volume of leachate (Liu et al. 2013).

Statistical analyses

Analysis of variance (ANOVA) using PROC MIXED (SAS Institute 2008) was conducted on soil, leachate and biomass results to determine significant cropping system, nutrient treatment effects and their interaction in each year. Assumption of normality distribution was checked using PROC UNIVARIATE. Since Shapiro–Wilk's normality test did not show normal distribution for leachate and soil measurements, the $\log_{10}$ transformed data was used to generate normal distribution of residuals and homogeneity of variance prior to statistical analysis. For total above-ground biomass and their nutrient uptakes as well as leachate, the statistical model included block (with four levels) as a random factor and treatments (five levels) and cropping systems (two levels) as fixed factors. For soil P, the statistical model included block (with four levels) as a random factor and treatments (five levels), cropping systems (two levels) and depth (six levels) as fixed factors with depth treated as a repeated measurement. The spatial power [SP(POW)] covariance structure was used in the model for the repeated measures data in which the depth intervals were unequal. Due to variation in manure application by hand a predefined 0.1 significant level was considered (Olatuyi et al. 2012; Zvomuya et al. 2003). Treatment differences were accepted if $P < 0.1$ using Tukey–Kramer method.

Results and discussion

Total above-ground biomass and P uptake

Total above-ground biomass and P uptake of the two cropping systems was compared in a full factorial analysis (Table 3). In 2009, there was a significant effect of cropping system on biomass as the canola crop produced significantly greater biomass than the grass (Table 3). There was no significant effect of manure treatment ($P > 0.1$) on biomass yield or P uptake, due to the similarity between the various manure treatments in the first year of the study. However, although not statistically significant ($P < 0.1055$), the solid manure resulted in the greatest P uptake, particularly for the canola. The control treatments of both annual and perennial cropping

Table 3 Above ground plant biomass and P uptake of canola and grass at harvest

Group means		Biomass (kg ha^{-1})			P uptake (kg ha^{-1})		
		2009	2010	2011	2009	2010	2011
Crop × manure							
Annual							
Liquid-N		11,732	9105 a	11,505 a	20.7	31.9a	28.6 ab
Liquid-P		11,634	7680 ab	12,315 a	21.6	21.1 b	21.6 bc
Solid-N		11,715	8610 ab	12,560 a	27.4	30.8 a	33.4 a
Solid-P		11,916	7400 ab	13,715 a	24.8	26.6 ab	28.5 ab
Control		10,397	5833 b	7155 b	19.1	18.2 b	15.9 c
Perennial							
Liquid-N		8195	10,865 a	10,476 a	19.2	40.8 a	26.2 a
Liquid-P		7983	9893 ab	9164 ab	18.3	30.7 bc	20.4 ab
Solid-N		7350	7838 ab	7629 ab	18.2	30.6 bc	22.0 ab
Solid-P		7293	10,978 a	9399 ab	18.7	36.1 ab	22.5 ab
Control		6848	7453 b	6392 b	15.4	24.2 c	16.7 b
Crop							
Annual[a]		11,479 a	7725 b	11,450 a	22.7	25.7 b	25.4 a
Perennial		7533 b	9405 a	8612 b	17.9	32.5 a	21.5 b
Manure							
Liquid-N		9964	9985 a	10,991 a	19.9	36.3 a	27.4 a
Liquid-P		9808	8786 a	10,739 a	19.9	25.9 cd	21.0 bc
Solid-N		9532	8223 ab	10,094 a	22.8	30.7 bc	27.7 a
Solid-P		9604	9188 a	11,557 a	21.8	31.4 ab	25.5 ab
Control		8622	6642 b	6773 b	17.3	21.2 d	16.3 c
Model effect	*df*	*P* value[b]					
Crop	1	0.0138	0.0298	0.0029	0.1271	0.007	0.0007
Manure	4	0.3926	0.0017	0.0001	0.1055	<0.0001	<0.0001
Crop × manure	4	0.8833	0.0233	0.0436	0.2343	0.0402	0.0082

[a] Canola: 2009 and 2011; Barley: 2010

[b] Means with the same letter within the column are not significantly different at $P < 0.1$ according to Tukey–Kramer test

systems also produced numerically the smallest biomass yield and P uptake.

In 2010 there was a significant crop effect, manure effect and crop × manure interaction for total biomass and P uptake (Table 3). Perennial grasses (9405 kg ha^{-1}) produced significantly greater biomass than the barley (7725 kg ha^{-1}). Similarly, P uptake by perennial grasses was significantly greater than by barley (32.5 vs. 25.5 kg ha^{-1}, respectively). The N-based manure application rate had the greatest biomass yield in the annual cropping system. Regardless of the forms of manure, the greatest P removal was in the N-based manure treatments (Table 3). This may reflect the cumulative effect of 2-year of manure addition (Table 2). The P-based solid manure and the N-based liquid manure had the highest grass yields with both manure treatment having significantly greater grass yield than the control (Table 3). A similar trend was observed for P uptake (Table 3). The grass yields on the N-based solid manure were numerically smaller but not statistically different from the other manure treatments. Nitrogen availability from the N-based solid manure might have limited yield as the manure supplied only 76 kg N ha^{-1} in 2010 (Table 2). The N-based liquid manure resulted in statistically greater P uptake in the grass than the P-based liquid manure, N-based solid manure and the control treatments. In 2010 the liquid manure application rate over-applied P (172 kg P ha^{-1}, Table 2).

In 2011, there was a significant crop effect, manure effect and crop × manure interaction on total biomass and P uptake (Table 3). Canola produced significantly greater biomass (11,450 kg ha^{-1}) than the grass (8612 kg ha^{-1}). This is reflected in the P uptake for these treatments. All manure treatments showed significant greater biomass than control plots in annual cropping system. Grass yields (Table 3) from the N-based liquid manure were significantly greater than the control. However, there was no significant difference between the N-based liquid pig manure treatment and other manure treatments. The same trend was observed for P uptake (Table 3). While the N-based solid manure treatment produced one of the greatest yields in the annual plots, it produced the smallest yield in perennial plots. The reason for these lower grass yields in the N-based solid manure treatment was probably due to surface application of the manure without incorporation by tillage, resulting in a reduced N mineralization (Kabiri et al. 2016; Martínez et al. 2017). The N-based liquid manure resulted in statistically greater P uptake in the grass than the control treatments.

Soil test phosphorus

Soil sampling and analyses indicated that the accumulation of Olsen P was in the upper layer of soil (0–0.15 m) and there was no evidence of significant P movement beyond this layer (Fig. 1). The STP levels decreased with depth, independent of treatment, reflecting the application of manure to the topsoil layer and crop P removal from deeper subsoil layers (Sadeghpour et al. 2016b). Miller et al. (2011) found maximum STP concentration within the 0–0.30 m depth and no treatment differences on soil P concentration below 0.30 m for different manure treatments after 9-year of manure application. Since most of the agronomic and environmental recommendations in Manitoba use residual P level within the top 0.15 m, the soil P data that was collected at the 0–0.15 m depth is the primary focus of the discussion herein.

In 2009, STP concentrations behaved similarly for both cropping systems (i.e. no crop effect or crop × manure interaction, Table 4). There was a significant effect of the manure treatment on STP concentrations at mid-season and at harvest. The significant manure treatment differences are based on pooled data for the annual and perennial cropping systems. The STP of control plots (Table 4), were agronomically high (> 15 mg Olsen P kg^{-1}) to very high (> 20 mg Olsen P kg^{-1}) according to the Manitoba Soil Fertility Guide (Manitoba Agriculture, Food and Rural Initiatives (MAFRI) 2007), indicating that the background P fertility of the site was high even without the addition of manure. The P-based solid manure treatment at harvest had significantly higher STP concentrations than the control and the P-based liquid manure treatment (Table 4). This was likely due to the greater quantity of P that was in the added solid manure (Table 2). The liquid manure provided much less P than the solid manure at 25 and 29 kg P ha^{-1} for the annual and perennial cropping systems,

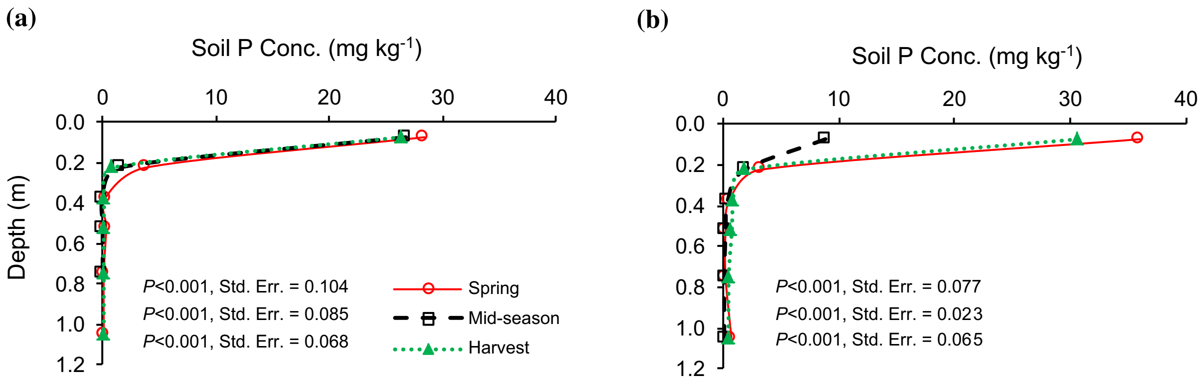

Fig. 1 Vertical distribution of Olsen P at spring, mid-season and harvest **a** 2010 and **b** 2011. The plots are amalgamation of the cropping systems and treatments

Table 4 The STP concentration (mg Olsen P kg^{-1}) within the first 0.15 m of soil in 2009, 2010 and 2011

Group means		Spring			Mid-season			Harvest		
		2009	2010	2011	2009	2010	2011[a]	2009	2010	2011
Crop × manure										
Annual										
Liquid-N		25.0	20.1 b	48.7	25.5	46.9	12.7	21.3	58.5 ab	42.2
Liquid-P		18.2	27.2 ab	19.3	25.0	19.4	5.5	23.8	16.6 c	20.9
Solid-N		32.9	46.5 a	69.8	35.7	49.5	25.4	31.1	65.7 a	55.2
Solid-P		25.3	24.4 ab	30.4	30.9	36.11	7.8	34.5	34.8 bc	26.4
Control		26.1	15.1 b	15.5	18.5	17.5	5.5	19.7	18.4 c	18.8
Perennial										
Liquid-N		31.0	21.5 ab	54.1	17.8	57.1	11.5	24.9	46.6 a	43.6
Liquid-P		25.9	16.1 b	13.5	19.0	13.5	3.2	17.9	9.3 b	13.6
Solid-N		23.1	26.1 ab	52.8	29.4	39.1	19.4	18.3	22.9 ab	41.2
Solid-P		29.0	38.0 a	43.1	29.2	30.3	7.5	29.7	30.4 ab	24.7
Control		21.4	15.7 b	16.4	21.8	11.6	4.2	17.3	13.4 b	18.1
Crop										
Annual		25.5	26.6	36.7	27.1	33.9	9.5 a	26.1	38.8 a	32.7
Perennial		26.1	23.5	36.0	23.4	30.3	7.4 b	21.6	24.5 b	28.3
Manure										
Liquid-N		28.9	20.8 c	51.4 ab	21.7 ab	52 a	12.1 b	23.1 ab	52.5 a	42.9 a
Liquid-P		22.0	21.6 bc	16.4 c	22.0 ab	16.4 b	4.2 d	20.9 b	12.9 d	17.2 b
Solid-N		28.0	36.3 a	61.3 a	32.5 a	44.3 a	22.2 a	24.7 ab	44.3 ab	48.2 a
Solid-P		27.1	31.2 ab	36.7 b	30.0 ab	33.2 ab	7.6 bc	32.1 a	32.6 bc	25.6 b
Control		23.8	15.4 c	16.0 c	20.2 b	14.6 b	4.2 cd	18.5 b	15.9 cd	18.47 b
Model effect	*df*	*P* value[b]								
Crop	1	0.8256	0.6210	0.8637	0.4714	0.5828	0.0673	0.3997	0.0013	0.3904
Manure	4	0.5047	< 0.0001	< 0.0001	0.0196	0.0002	< 0.0001	0.0035	< 0.0001	< 0.0001
Crop × manure	4	0.2029	0.0024	0.2735	0.6835	0.7312	0.7528	0.1745	0.0247	0.3486

[a] Log transformed data

[b] Means with the same letter within the column are not significantly different at $P < 0.1$ according to Tukey–Kramer test

respectively (Table 2), and the STP levels from these plots was not statistically different from the control.

In 2010, there was a significant interaction between the cropping system and manure treatment on STP concentrations in spring and at harvest (Table 4). For this reason, the effect of the manure treatment on spring and harvest STP concentrations was analyzed for the annual and perennial cropping systems separately.

At harvest, 2010, the STP concentrations were greater in the annual plots than in the perennial plots (Table 4). Higher crop P uptakes for the perennial system in 2010 (Table 3) may explain, in part, the lower STP levels in the perennial system. Brookes et al. (1984) reported higher capacity of perennials for building P in the microbial biomass than annuals due to favorable moisture conditions in perennial rotations. In annual cropping system, the N-based manure applications resulted in higher STP levels than the control. In 2010, the liquid manure had a high solid content and high P concentration that supplied about 172 kg P ha^{-1} (Table 2). Therefore, very high STP level could be expected from the N-based liquid manure. The P concentration of the solid manure was not measured; however, the high STP concentration of this treatment was apparent in the mid-season that was measured after manure application. For the perennial cropping system, the N-based liquid manure application rate resulted in the highest STP concentration at harvest. This treatment resulted in significantly greater STP concentration than the P-based liquid manure treatment and the control; however, it was not significantly different from the N- and P-based solid manure treatments.

In 2011 manure treatments affected STP concentration at the three sampling periods and the effect of manure treatments was consistent for both cropping systems (i.e. no crop × manure interaction). The STP concentration for perennial system was significantly lower than for the annual system at mid-season only (Table 4). The N-based manure treatments resulted in the highest STP at harvest in 2011. The P-based treatments resulted in significantly lower STP levels than the N-based rates at all three sampling events. The STP in the P-based treatment was not significantly different from the control. Comparison of Olsen-extractable P in the control plot at three different sampling times showed the temporal changes of soil P. The seasonal variation in the control plot and other treatments was greater in 2011 than in 2010. The reason for reduced fluctuation in STP concentration in 2010 can be related to a relatively high soil P concentration during the wet season after snowmelt in spring and after heavy precipitation in summer. The high moisture content of soil and anaerobic conditions results in decrease of soil redox potential and thereby increase of calcium phosphate minerals solubility in alkaline soils (Amarawansha et al. 2015). In contrast to our 3-year study results, Eghball (2003) reported accumulation of P at the 0.30–0.60 m of the soil profile in a sandy loam after 20-year of manure application. Therefore, with long term application of manure, P may finally be subjected to leaching which often occurs on a time scale of decades or more (Radcliffe and Cabrera 2007). Because increasing STP results in an increase of P concentration in runoff, STP build-up in N-based manure treatments should be managed through field rotation.

Compared to P-based treatments, annual applications of both forms of manure at an N-based rate, increased STP levels by twofold, after 3-year of manure application. This increases the risk of P loss through surface runoff, particularly during spring snowmelt. Studies in southern Manitoba, Canada showed that increases in soil P resulted in greater concentrations of dissolved P in runoff, the predominant form of P in snowmelt-dominated surface runoff from cold-climate regions such as Manitoba (Liu et al. 2014). Similarly, Sadeghpour et al. (2016a) reported that STP increased four- and six-fold for N-based and two- and four-fold for P-based liquid dairy and composted dairy solid manure, after 5-year corn (*Zea mays* L.) field study in Aurora, NY.

Phosphorus leached below the root zone

The leached water that was lost below the root zone of the annual crop was numerically greater than the water lost below the perennial crop in all 3-year, however, the differences were not statistically significant (Table 5). The absence of a significant crop effect on the quantity of water leached below the root zone was unexpected. Deeper rooting depth and greater water use by perennial crops have been shown to decrease the water available for leaching (Entz et al. 2001; Mueller et al. 2005; Hatfield et al. 2001). The amount of precipitation received during the growing season in 2010 was 420 mm, which was 154% of the 30-year normal growing season precipitation. The large amount of precipitation led to a leaching loss in the range of 0.18–0.33 m in the perennial and 0.23–0.36 m in the annual cropping system (Table 5), however, there was no statistical difference between these amounts.

The quantity of P that was measured in the leachate was negligible with no significant effects of cropping system, manure or crop × manure interaction. This is consistent with the soil P data that showed little movement beyond the 0–0.15 m depth interval. The mass of P that was leached from this sandy loam soil was smaller than the 23–148 and 40–165 g P ha^{-1} year^{-1} that were reported by Bergström and Kirchmann (2006) and Sørensen and Rubæk (2012), respectively, from a sandy soil after application of liquid pig manure. Our data however, showed that the mass of leached P in the manured plots increased from 2009 to 2011, an indication of the cumulative effect of manure application (Table 5).

In 2009 and 2010 there was no significant effects of cropping system, manure or crop × manure interaction on flow weighted mean concentration of P (FWMCP). However, in 2011, there was a significant effect of manure on FWMCP ($P < 0.1$). The FWMCP was greater for the liquid manure treatments than the N-based solid manure treatment but was not

Table 5 Leaching of water and P from annual and perennial plots in 2009, 2010 and 2011

		Water (m)		P (g ha^{-1})		FWMCP[a] (mg L^{-1})	
		Annual	Perennial	Annual	Perennial	Annual	Perennial
2009							
Liquid-N		0.108	0.052	2	1	0.002	0.003
Liquid-P		0.067	0.044	3	3	0.004	0.008
Solid-N		0.089	0.078	8	2	0.010	0.003
Solid-P		0.116	0.075	15	3	0.015	0.005
Control		0.073	0.091	14	4	0.020	0.005
Model effect	*df*	*P* value[b]					
Crop	1	0.3101		0.254		0.3086	
Manure	4	0.3267		0.1262		0.1283	
Crop × manure	4	0.3746		0.5733		0.1092	
2010							
Liquid-N		0.226	0.188	10	15	0.007	0.008
Liquid-P		0.321	0.297	30	10	0.011	0.006
Solid-N		0.291	0.182	10	10	0.004	0.010
Solid-P		0.362	0.304	40	10	0.015	0.005
Control		0.305	0.328	20	20	0.009	0.006
Model effect	*df*	*P* value					
Crop	1	0.543		0.2148		0.5621	
Manure	4	0.4228		0.6427		0.9883	
Crop × manure	4	0.9217		0.6554		0.4022	
2011							
Liquid-N		0.219	0.174	50	40	0.022	0.027
Liquid-P		0.323	0.280	50	100	0.022	0.024
Solid-N		0.221	0.236	30	20	0.012	0.012
Solid-P		0.357	0.272	60	40	0.020	0.014
Control		0.313	0.291	70	30	0.027	0.014
Model effect	*df*	*P* value					
Crop	1	0.5472		0.5828		0.6341	
Manure	4	0.628		0.3462		0.0753	
Crop × manure	4	0.9788		0.7098		0.4532	

[a] Flow weighted mean concentration of phosphorus

[b] Probability value is significant at $P < 0.1$

significantly different from the control. For example, the FWMCP of N-based liquid manure treatment for both annual and perennial cropping systems in 2011 was about 10 times greater than those in 2009. This is another indication of the cumulative effect of manure application on the mass of P that is lost in the leachate. Although, very low concentrations of P (0.025–0.05 mg P L^{-1}) are sufficient to cause eutrophication and algae growth in some surface waters (Flaten et al. 2003), P concentrations in leachate did not exceed this threshold during the 3-year of study.

Overall, the infrequent sampling of leachate and its nutrient composition can create uncertainty in the estimated annual nutrient load (Williams et al. 2015). Working with tile drainage in Ohio, USA and Ontario Canada Williams et al. (2015) concluded that the level of uncertainty in annual nutrient load estimates increased with increasing sampling interval for all of the load estimation algorithms tested. Although we quantitatively removed all the leachate in the lysimeter at each sampling interval, the possibility exists that sampling the lysimeter 3–5 times in a year can create error in the annual nutrient load that we have estimated.

Conclusions

Our study showed that the accumulation of P following manure application was restricted to the upper layer of soil (0–0.15 m) and there was no evidence of an increase in STP concentration below this layer with either the N-based or P-based manure treatment. By the third year of the study, STP levels in the solid and liquid P-based treatments were not significantly different from the control. However, annual applications of both forms of manure at an N-based rate resulted in a significant increase in STP over the P-based and the control. The STP values in the N-based treatments were twice as high as the values in the corresponding P-based treatments. Because the risk of P loss in surface runoff increases with STP, accumulation of P should be managed by rotating fields when N-based manure application rates are applied. Our results showed that P concentrations in leachate did not exceed the threshold of 0.025 mg L^{-1} total P for lakes, and 0.05 mg L^{-1} total P for streams and rivers in Manitoba. Therefore, the short-term risk of P leaching and water contamination is low even with N-based manure managements at this site.

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