



Agri-environmental implications of N- and P-based manure application to perennial and annual cropping systems

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Received: 10 January 2021 / Accepted: 7 December 2021 / Published online: 19 February 2022
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Abstract Continuous manure application based on crop nitrogen (N) requirements could substantially increase field nutrient losses from croplands. Although phosphorus-based (P) manure application is an alternative, crops may suffer from potential microbial P immobilization and fixation of P in soil. A three-year study (2012–2014) was carried out in Manitoba, Canada, to evaluate the agronomic and environmental benefits and tradeoffs between N- and P-based liquid and solid swine manure applications on previously established (2009) annual (ACS) and perennial (PCS) cropping systems. The N-based solid manure produced greater aboveground biomass and grain yields of barley than the unfertilized control in the ACS. The N-based liquid manure produced greater biomass than the control in the PCS. Phosphorus-based treatments produced statistically similar canola oilseed grains as the N-based treatments. Seeding the PCS to canola in 2013 produced greater aboveground biomass yields than the ACS; however, the canola oilseed yields were not significantly different between the two systems.

The N-based solid manure application increased Olsen P by approximately 30 mg kg^{-1} in both cropping systems during the three-year study period. Both N- and P-based liquid manure treatments and the N-based solid manure treatment lost significantly greater nitrate through leaching than the control in 2013, when most leaching losses occurred. Our study also showed that some of the environmental benefits of the perennial cropping system, such as reduced nitrate leaching, could be lost when converted to an annual cropping system.

Keywords Swine manure · Manure source · Barley · Forage · Nitrate leaching · Soil test phosphorus · Water quality

Introduction

Land application of manure enhances soil productivity by supplying plant nutrients and improving soil physical characteristics such as soil structure, aeration, porosity and water holding capacity (Adesanya et al. 2016; Cai et al. 2019; Williams et al. 2017). However, frequent application of manure and manure application at a rate that exceeds crop requirement can increase the potential of nutrient loss from agricultural soil to ground- and surface water (Nikiema et al. 2013; Kokulan et al. 2021a). Thus, excess nutrients from

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10705-021-10187-w>.

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agricultural systems are one of the most important current sources of pollution for several surface and groundwater bodies (Schindler et al. 2012).

Several studies have shown that repeated land application of animal manure increased the risk of nitrate ($\text{NO}_3\text{-N}$) leaching through the soil profile, and potentially, into the groundwater due to its solubility and mobility (Bakhsh et al. 2009; Miller et al., 2020; Nikiema et al. 2013). Among animal manures, swine manure poses a greater risk of phosphorus (P) pollution when applied according to crop N requirements due to its smaller N:P ratio (Schindler et al. 2012). Continuous swine manure application results in over-application of P, and consequently, in a buildup of Olsen P at the soil surface (Karimi et al. 2018a; Kokulan et al. 2021a). As Olsen P increases, the concentration of P in the surface runoff also increases (Wilson et al. 2019). However, recent studies have shown that the downward movement of P does also occur once the soil P exceeds a certain threshold, even though P is regarded as a relatively immobile nutrient (Duncan et al. 2017; King et al. 2015). Large and continuous application of fertilizers (organic or inorganic) can result in soil P buildup, which consequently increases the potential of P leaching (King et al. 2015). Also, manure application could reduce the P retention capacity of soils by increasing the labile P fractions and exhausting P retention sites, subsequently rendering P more mobile (Simard et al. 1995; Ajiboye et al. 2004). Understanding the environmental consequences of manure application under different management scenarios is essential in regions like the Canadian Prairies, where agricultural runoff-related pollution is an ongoing issue (Schindler et al. 2012).

Nutrient leaching also varies with cropping systems. In general, annual cropping systems (ACS) have been reported to result in greater $\text{NO}_3\text{-N}$ leaching losses than perennial cropping systems (PCS) (Karimi et al. 2017). Randall et al. (1997) reported a 35-fold annual $\text{NO}_3\text{-N}$ loss from an ACS compared to a PCS. The efficiency of nutrient utilization by annual crops remained low regardless of cropping strategies and was significantly influenced by weather conditions (Dinnes et al. 2002). The extensive rooting system of perennial crops enables them to efficiently capture soil nutrients, thus minimizing leaching losses (Lasisi et al. 2018). Over time, PCS can increase soil organic carbon stocks (Ledo et al. 2020). As such, converting a PCS to ACS may be expected to boost the yields of the

annual crops due to increased nutrient availability. However, converting a PCS into an ACS could also result in substantial gaseous (mainly C and N) and leaching ($\text{NO}_3\text{-N}$) losses (Moore et al. 2020; Adelekun et al. 2019). However, this aspect of cropping system management is understudied in regions like the Canadian Prairies.

Phosphorus-based manure application has been suggested as an alternative to N-based management to reduce potential P pollution. However, the application of manure to meet the annual P requirements of the crop most often does not supply adequate N for optimum yields. Therefore, for soils with high P, it is recommended that manure is applied to meet the first crop's N requirements in the rotation. The manure must not be applied until subsequent crops have removed the additional soil P. In subsequent years, synthetic N fertilizer is applied to meet the crop N requirement (Government of Manitoba 2009).

The majority of studies that compared the agronomic potential of N- and P-based nutrient management systems did not find significant yield reductions by the P-based system (e.g., Karimi et al. 2018b; Toth et al. 2006). However, N-based manure management resulted in greater P accumulation in the topsoil (Miller et al. 2011; Maguire et al. 2008) when compared to P-based systems, potentially due to larger P application rates. In an earlier study, Karimi et al. (2017) also reported that the P-based solid manure application reduced the risk of $\text{NO}_3\text{-N}$ leaching relative to N-based treatments. However, the long-term implications of P-based systems on $\text{NO}_3\text{-N}$ leaching are unclear as the P-based systems continue to receive inorganic N supplements. Despite the benefits mentioned above, the P-based manure application may also produce smaller crop yields than the N-based treatments over time due to microbial P immobilization and P fixation in the soil (Shen et al. 2011). However, studies that assessed the agronomic efficiency of P-based manure application relative to crop yields and N and P leaching are generally lacking.

In this study, we hypothesized that the annual and perennial cropping systems that received P-based manure application could produce smaller yields than the N-based manure application due to soil P immobilization over time. However, continuous application of N-based manure could result in surface accumulation of P and elevated $\text{NO}_3\text{-N}$ leaching relative to P-based application. We also hypothesized that

converting a perennial cropping system to an annual cropping system for a short period could boost yields due to increased nutrient availability. However, the conversion could potentially elevate nutrient leaching risk. We evaluated crop yield, soil P concentration, and N and P in leachate to (1) assess the agronomic and environmental potential of P-based and N-based liquid and solid swine manure treatments on an annual cropping system and (2) to assess the agronomic and environmental resiliency of a perennial system treated with N- and P-based swine manure when cropped with an annual crop (canola) for one growing season.

Material and methods

Description of the experimental site

The experimental site was located on a moderately well-drained Orthic Black Chernozem (Udic Boroll) in Carman, Manitoba, Canada. In the fall of 2006, the entire experimental area was seeded to 50% alfalfa, 34% timothy and 16% orchard grass and maintained until the spring of 2009, when the experiment was initiated. At the study initiation, the alfalfa on the perennial plots was killed by applying clopyralid and 2-methyl-4-chlorophenoxy-acetic acid (MCPA) herbicides at the rates of 0.84 L ha⁻¹ and 0.98 L ha⁻¹, respectively, leaving the perennial plots with 68% timothy and 32% orchard grass. The alfalfa-timothy-orchard grass on the annual plot was also killed and was ploughed into the soil. The experimental area consisted of 40 sub-plots of 10 m × 10 m with a field core lysimeter installed at the southeast corner of each sub-plot in the summer of 2006 for direct measurement of water movement and nutrient leaching.

The experiment, as established in 2009, was a split-plot design in which the main plots consisted of two cropping systems (ACS and PCS) and five experimental treatments, namely: N-based liquid swine manure (NLM), P-based liquid swine manure (PLM), N-based solid swine manure (NSM), P-based solid swine manure (PSM) and an unfertilized control, constituted the sub-plots. Each experimental treatment was replicated four times. The N-based treatments received annual manure application rates that targeted crop N requirements. The P-based treatments received one dose of manure application in 2009 at a rate estimated to supply five years of crop P requirements,

while urea was applied in the subsequent years to meet crop N requirements. The experimental setup and treatment application from 2009 to 2011 have been provided by Karimi et al. (2018b). The ACS was seeded to canola-barley rotation between 2009 and 2014, while the timothy/orchard grass was maintained on the PCS between 2009 and 2012. The PCS was ploughed under in the spring of 2013 and was converted to ACS by seeding it to canola. The converted perennial plots were reseeded with a timothy/orchard grass mixture in spring 2014.

Manure/urea treatments were based on the residual soil NO₃-N concentration determined in the previous fall. The N-based treatments received swine manure in all study years. In 2009, swine manure delivered 82 kg ha⁻¹ P to P-based annual plots, whereas the P-based perennial plots received 90 kg ha⁻¹ P. Urea was applied to P-based treatments from 2010 to 2013 based on the crop requirement and residual soil NO₃-N content (Table S1). However, P-based treatments did not receive N fertilization in 2014 due to logistical reasons. The liquid manure was applied manually from 20 L jugs. The solid manure was evenly spread with a pitchfork and a rake. In annual plots, the manure was incorporated with a rototiller to a depth of 0.1 m before seeding.

Weather

The study site received below-normal annual precipitation in all three years compared to the long-term 10 year average (505 mm). Years 2013 and 2014 received 399 and 431 mm annual precipitation, respectively. The year 2012 was drier, receiving only 340 mm. The growing season (May to September) precipitation for 2012, 2013 and 2014 were 185, 271 and 344 mm. Exceptionally high monthly precipitation (> 100 mm) was recorded in May of 2013 (167 mm) and in June (117 mm), and August (122 mm) of 2014 (Fig. S1). About 130 mm precipitation was recorded between May 17th and May 31st, 2013, coinciding with manure application. Only 41 and 23 mm precipitation was received in 2012 and 2014, respectively, during this same period.

Field and laboratory procedures

Soil samples were collected three times during the growing seasons (spring, mid-season, and harvest) of

the study years. Sampling was done at six depth intervals of 0–0.15, 0.15–0.3, 0.3–0.45, 0.45–0.6, 0.6–0.9 and 0.9–1.2 m for spring and harvest using a Giddings mounted on a tractor and at five depths of 0–0.15, 0.15–0.3, 0.3–0.45, 0.45–0.6, 0.6–0.9 m for mid-season using a Dutch auger. Two soil core samples were taken from each plot, composited and thoroughly mixed. Gravimetric moisture content was determined by oven drying approximately 20 g of soil sample at 105 °C for 48 h. Olsen-P was measured by extracting the moist soil samples with NaHCO₃ (Olsen and Sommers 1982), and P in the extract was determined using the molybdate blue colorimetric method of Murphy and Riley (1962).

Aboveground biomass was sampled twice each year from the perennials (at mid-season and harvest) and once each year (at harvest) from the annuals from four randomly selected areas in each plot using a 0.25 m² quadrant. The plant material was collected into cloth bags, which were hung in a drying room (with warm, constant airflow at 32 °C) to dry at least for two weeks. After drying, the aboveground biomass was weighed and subsampled for the perennial grass. The canola and barley were mechanically separated in grains/oilseeds and straw and weighed. A subsample of each plant tissue was ground and analyzed for total P using the wet oxidation technique of Akinremi et al. (2003) and total N using the wet oxidation method described by Parkinson and Allen (1975).

Lysimeters were checked frequently during the growing season (April to September) and after the major precipitation events. Leachates were not produced from November to March due to sub-zero air temperatures and a subsurface soil-ice layer (Kokulan et al. 2019, 2021b). The total volume of the leachate was measured, and a subsample was stored at – 18 °C. Total P and NO₃-N in the leachate were measured within a week of sample collection as previously described for the soil extracts.

Statistical analyses

Analysis of variance using PROC MIXED (SAS University Edition) was conducted on the aboveground plant biomass, grain/oilseed yield and nutrient removal, Olsen P and leachate to determine the effect of cropping system, manure treatments and their interactions in each year. The cropping systems and treatments were considered fixed factors whereas the

block was considered a random factor. Statistical analysis was not performed for leachate collected in 2012 due to smaller volumes. The normality was checked according to Shapiro–Wilk’s normality test with Proc Univariate procedure. Non-normal data were log₁₀ transformed. Treatment means were compared using the Tukey–Kramer test at a probability level of $P \leq 0.1$.

Results

Crop yields

The aboveground biomass did not significantly differ between the ACS and PCS in 2012 (Table 1). In 2013, the biomass yield of canola was significantly greater in the converted perennial plot than in the annual plot. However, the oilseed yield was statistically similar between both cropping systems (Table 2). The PCS produced significantly smaller biomass than the ACS in 2014 when it was cropped again with perennial grass (Table 1).

The interaction of manure and crop was significant for all three study years, suggesting that the effect of manure on biomass was dependent on the cropping system (Table 1). The NSM treatment produced significantly greater grain yields than the control in the ACS when barley was cultivated in 2012 and 2014 (Table 3). Barley grain yields of the NSM treatment were also significantly greater than the PSM treatment in 2012. The PSM produced significantly higher grain yields in 2014 than the control treatment. In the PCS, the NSM and PSM treatments produced statistically similar perennial grass yields in 2012 (Table 1). The canola biomass and oilseed yields were statistically similar between NSM and PSM treatments in the ACS and the converted PCS in 2013 (Tables 1 and 2).

The NLM and PLM treatments produced statistically similar biomass under both ACS and PCS in 2012 and 2013 (Table 1). The NLM treatment produced significantly greater biomass yields than the control for the PCS in all three years (Table 1). In 2014, the NLM treatment also produced significantly greater barley grain yields relative to the control treatment in the ACS (Table 3). The PLM treatment and the control produced statistically similar biomass yields in both ACS and PCS in 2012 and 2014. However, the canola biomass and oilseed yields of the

Table 1 Aboveground biomass and N and P uptake by barley (2012 and 2014, annual), canola (2013) and grass (2012 and 2014, perennial) from 2012 to 2014

Group means	Biomass (kg ha ⁻¹)			N uptake (kg ha ⁻¹)			P uptake (kg ha ⁻¹)			
	2012	2013	2014	2012	2013	2014	2012	2013	2014	
Crop × manure										
<i>Annual</i>										
NLM ^a	8391ab	14647a	15272a	113ab	290a	201	24a	42ab	36	
PLM	7518ab	14147a	10540b	110abc	228ab	108	14b	28c	12	
NSM	9501a	15963a	16480a	135a	298a	250	30a	47a	44	
PSM	7238b	16690a	14840a	97bc	294a	168	13b	34bc	25	
Control	6609b	11635a	8973b	74c	166b	84	16b	28c	13	
<i>Perennial</i>										
NLM	10635a	19637a	13359a	170a	396a	271	32a	57a	41	
PLM	8273ab	16505ab	9602bc	142a	322ab	159	21bc	34b	20	
NSM	8219ab	18370ab	12153a	146a	383ab	283	28ab	61a	46	
PSM	9595a	15300b	10422b	158a	310b	179	25ab	36b	27	
Control	5065b	10107c	8526c	56b	126c	123	14c	24c	18	
<i>Crop</i>										
Annual	7851	14,616 b	13221a	106b	255b	162b	19b	36b	26b	
Perennial	8357	15,984 a	10812b	134a	307a	201a	24a	42a	30a	
<i>Manure</i>										
NLM	9513a	17,142 a	14316a	141a	343a	236a	28a	50a	38b	
PLM	7895a	15,326 a	10071b	126a	275b	130bc	18b	31bc	16d	
NSM	8860a	17,167 a	14317a	141a	341a	266a	29a	54a	45a	
PSM	8416a	15,995 a	12631a	128a	302ab	173b	19b	35b	26c	
Control	5837b	10,871 b	8749b	65b	146c	103c	15b	26c	15d	
Model effect	df	P value ^b								
Crop	1	0.291	0.065	< 0.01	< 0.001	0.001	0.005	< 0.001	< 0.001	0.004
Manure	4	< 0.001	< 0.001	< 0.01	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Crop × manure	4	0.029	0.033	0.070	0.003	0.014	0.710	0.070	0.003	0.680

^aNLM N-based liquid manure; PLM P-based liquid manure; NSM N-based solid manure; PSM P-based solid manure. P-based treatments did not receive urea in 2014

^bMeans with different letters within the column and a cropping system are significantly different at $P < 0.1$ according to Tukey–Kramer test

PLM treatment were significantly greater than the control in the converted PCS in 2013 (Tables 1 and 2).

The crop N and P uptake was also significantly greater for the NSM treatment than the control under both ACS and PCS in all three years (Table 1). The NSM removed significantly greater N than the PSM in the ACS in 2012. The P uptake from the NSM was also greater than the PSM treatment in the ACS for 2012 and 2013 and in the PCS in 2013. The NLM treatment also showed significantly greater N and P uptake than

the control under both ACS and PCS in all three years (Table 1). In contrast, the aboveground N and P uptake from the PLM treatment were statistically similar to the control under the ACS in all three years.

Olsen phosphorus

The surface (0–0.15 m) Olsen P concentration was significantly greater for both NLM and NSM treatments in all seasons relative to the control treatment

Table 2 Canola oilseed weight, N and P uptake and N and P concentration in 2013

	Seed (kg ha ⁻¹)	N removal (kg ha ⁻¹)	N concentration %	P removal (kg ha ⁻¹)	P concentration %	
Crop × manure						
<i>Annual</i>						
NLM ^a	4265a	184a	4.31a	31	0.72	
PLM	4043a	166ab	4.08ab	24	0.59	
NSM	4443a	188a	4.24a	33	0.74	
PSM	4532a	188a	4.16ab	27	0.60	
Control	3779a	114b	3.47b	24	0.63	
<i>Perennial</i>						
NLM	5038a	217a	4.3a	36	0.72	
PLM	4213a	184a	4.36a	25	0.59	
NSM	4465a	200a	4.48a	33	0.74	
PSM	4306a	183a	4.25a	27	0.62	
Control	2895b	98b	3.39b	20	0.69	
<i>Crop</i>						
Annual	4235	173	4.08	27.8	0.66	
Perennial	4183	176	4.16	28.2	0.67	
<i>Manure</i>						
NLM	4651a	201a	4.31a	34a		
PLM	4128a	175a	4.22a	24bc	0.72a	
NSM	4454a	194a	4.36a	33a	0.59c	
PSM	4418a	186a	4.21a	27b	0.74a	
Control	3273b	112b	3.55b	22c	0.61c	
Model effect	df	<i>P</i> value ^b				
Crop	1	0.956	0.522	0.432	0.623	0.266
Manure	4	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Crop × manure	4	0.079	0.085	0.077	0.131	0.807

^aNLM N-based liquid manure; PLM P-based liquid manure; NSM N-based solid manure; PSM P-based solid manure

^bMeans with different letters within the column and a cropping system are significantly different at $P < 0.1$ according to Tukey–Kramer test

(Table 4). The Olsen P (0–0.15 m) at harvest was significantly greater for the NSM treatment than the NLM treatment in 2012 and 2014 (Table 4). The surface Olsen P was significantly smaller for the PSM than the NSM in all seasons. Similarly, the Olsen P was significantly smaller for the PLM treatment than the NLM in all seasons. In fact, the Olsen P concentration for the PLM treatment in the mid-season and at the harvest was statistically similar to the control treatment.

The conversion of the PCS to ACS in 2013 increased the Olsen P at the surface for the N-based

treatments from the harvest of the previous year (2012) (Fig. 1, Table 4). The Olsen P at the surface increased from 36 (± 14) to 73 (± 18) mg kg⁻¹ (mean, \pm standard deviation) for the NLM treatment and from 50 (± 5) to 79 (± 7) mg kg⁻¹ for the NSM treatment from the harvest of grasses in 2012 to the harvest of canola in 2013. No significant change in Olsen P was observed for the P-based treatments during that conversion.

Olsen P was less than 15 mg kg⁻¹ P at the 0.15 to 0.3 m depth for all treatments in 2012 and 2013 in both cropping systems (Fig. 1). However, Olsen P at 0.15 -

Table 3 Barley seed weight, N and P uptake and N and P concentration in 2012 and 2014

		<i>Grain (kg ha⁻¹)</i>	<i>Nitrogen removal (kg ha⁻¹)</i>	<i>N concentration (%)</i>	<i>Phosphorus removal (kg ha⁻¹)</i>	<i>P concentration (%)</i>	
2012							
		NLM ^a	3510ab	79ab	2.26a	18ab	0.51a
		PLM	3361ab	79ab	2.33a	12bc	0.35b
		NSM	4434a	99a	2.24a	20a	0.44ab
		PSM	3014b	67b	2.24a	11c	0.36b
		Control	3208b	60b	1.87b	13bc	0.4ab
Model effect	d.f.			<i>P value^b</i>			
Manure	4	0.031	0.014	0.001	0.007	0.050	
2014							
		NLM	7382a	145ab	1.93ab	15ab	0.20ab
		PLM	4244b	79ab	1.78b	7b	0.16b
		NSM	8693a	194a	2.22a	19a	0.22a
		PSM	7180a	132ab	1.81ab	14ab	0.19b
		Control	4076b	65b	1.59b	8b	0.19b
Model effect	d.f.			<i>P value</i>			
Manure	4	0.031	0.012	0.018	0.008	0.001	

^aNLM N-based liquid manure; PLM P-based liquid manure; NSM N-based solid manure; PSM P-based solid manure. P-based treatments did not receive urea in 2014^bMeans with different letters within the column and a cropping system are significantly different at $P < 0.1$ according to Tukey–Kramer test

0.3 m increased to $17 (\pm 2) \text{ mg kg}^{-1}$ at harvest in 2014 for the NSM treatment in the ACS whereas it further increased to $41 (\pm 20) \text{ mg kg}^{-1}$ for the NSM and to $16 (\pm 12) \text{ mg kg}^{-1}$ for the NLM treatment in the PCS at the same period. The accumulation of P within the 0.3–0.12 m depth interval was small ($< 15 \text{ mg ha}^{-1}$) regardless of the manure treatment or cropping system during this study period.

Nutrient leaching

The significant variability observed between the N- and P-based treatments for the Olsen P at the surface (0–0.15 m) was not reflected in the leachate collected by the lysimeters (Table S1). No significant treatment effect was observed for flow-weighted mean total P (TP) concentration and TP leaching losses in any study years. The annual TP leaching losses were generally less than 0.05 kg ha^{-1} for N- and P-based liquid manure treatments. Nitrogen- and P-based solid manure treatments lost about 0.05 to 0.1 kg ha^{-1} TP via leachate when canola was cropped in the PCS plots in 2013.

In 2013, the leachate FWM $\text{NO}_3\text{-N}$ concentration and load were significantly greater for the N-based treatments than the control (Table 5). Although FWM $\text{NO}_3\text{-N}$ of the PLM was not significantly different than the control, it also lost significantly greater $\text{NO}_3\text{-N}$ in the leachate in 2013 relative to the control. The $\text{NO}_3\text{-N}$ concentration was elevated in both P-based treatments and the NLM treatment in 2014 but did not translate into significant $\text{NO}_3\text{-N}$ leaching losses.

Despite the conversion, the FWM $\text{NO}_3\text{-N}$ concentration and leaching losses were smaller from the converted perennial plots than the annual plots in 2013 (Table 5). However, all manure treatments lost greater $\text{NO}_3\text{-N}$ by leaching relative to the control from the PCS in 2013 (Table 5). In contrast, the FWM $\text{NO}_3\text{-N}$ concentration and leaching losses from the PCS were significantly greater in 2014 than the ACS (Table 5). In 2014, the FWM $\text{NO}_3\text{-N}$ concentration in the leachate from the PCS plots increased by a factor of 3 in the NLM treatment and by a factor of 2 in the NSM treatment compared to 2013. Similarly, FWM $\text{NO}_3\text{-N}$ concentration increased by a factor of 3 in the PLM and PSM plots at the same time.

Table 4 Olsen P concentration at surface (0–0.15 m depth)

Group means	Spring			Mid-season			Harvest			
	2012	2013	2014	2012	2013	2014	2012	2013	2014	
Crop × manure										
<i>Annual</i>										
NLM ^a	50.5	40.6	54.1b	44.1	46.4	57.0	43.8	52.9	59.5	
PLM	23.7	16.5	20.8 cd	21.5	20.3	16.9	22.8	17.7	25.6	
NSM	64.4	74.2	100.4a	63.0	64.0	81.1	54.0	76.2	94.5	
PSM	33.0	27.1	31.3c	25.1	34.4	30.2	28.7	14.8	46.6	
Control	20.5	19.8	13.0d	17.3	15.3	18.9	17.3	10.5	16.5	
<i>Perennial</i>										
NLM	52.7	37.0	81.7b	54.6	64.7	56.3	35.7	72.6	62.3	
PLM	16.5	10.1	16.6c	14.8	13.4	11.3	15.9	13.4	14.2	
NSM	64.4	73.5	108.1a	56.5	50.7	91.5	49.8	79.4	93.3	
PSM	29.4	25.7	23.8c	24.2	26.1	31.1	24.3	25.7	43.8	
Control	17.2	17.3	11.5c	17.2	13.8	14.4	16.3	11.7	15.1	
Crop										
Annual	38.4	32.7	43.9b	34.2	33.7	40.8	33.5a	40.6	48.5	
Perennial	36.0	35.6	51.3a	33.5	36.1	40.9	28.4b	34.4	45.7	
Manure										
NLM	51.6ab	38.8b	69.8b	49.3a	55.5a	56.7b	39.7b	62.7a	60.8b	
PLM	20.1c	13.3d	19.5d	18.2b	16.9c	14.1c	19.4 cd	15.6b	19.9d	
NSM	64.4a	73.8a	106.7a	59.8a	57.4a	86.3a	52.3a	77.8a	93.9a	
PSM	31.2bc	23.4c	27.2c	24.7b	30.3b	30.6c	26.5c	20.2b	45.2c	
Control	18.8c	18.6d	14.8e	17.3b	14.7c	16.7c	16.8d	11.1b	15.8d	
Model effect	df	P value ^b								
Crop	1	0.71	0.26	0.020	0.89	0.59	0.99	0.039	0.31	0.59
Manure	4	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Crop × manure	4	0.99	0.96	0.002	0.84	0.21	0.96	0.9	0.74	0.93

^aNLM N-based liquid manure; PLM P-based liquid manure; NSM N-based solid manure; PSM P-based solid manure

^bMeans with different letters within the column and a cropping system are significantly different at $P < 0.1$ according to Tukey–Kramer test

Discussion

Crop yields were influenced by manure types and forms

The crop yields were affected by the manure management (N- versus P-based), by the form of the manure (solid versus liquid) and by the cropping system (ACS versus PCS). The yield advantage shown by the N-based treatments could be due to the increased availability of N and P as indicated by greater crop N and P uptake. Although the NSM treatment did not

produce significant yields in the previous years (2009–2011, Karimi et al. 2018a), it produced the greatest barley yields and perennial biomass (2013 and 2014) in the current study. The surface application of solid manure without incorporation via tillage could have been responsible for the poor performance of the NSM treatment in the earlier years through the immobilization of N in the straw (Martinez et al. 2017). Over time, more nutrients from solid manure could have been made available through mineralization. The NLM treatment produced the greatest perennial grass yields. Similar results were reported

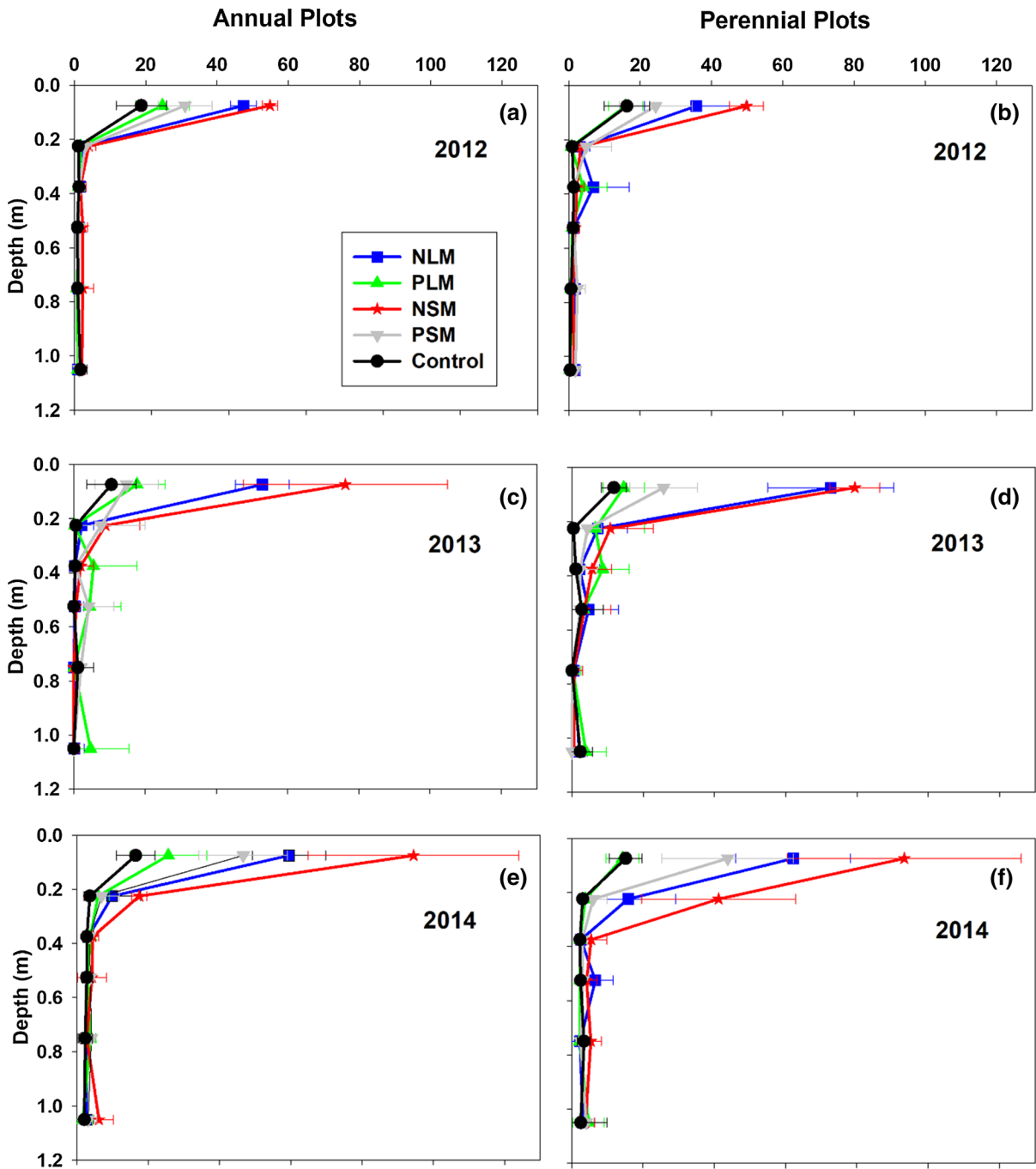


Fig. 1 Olsen P concentration along the soil profile at the harvest for the annual cropping system in 2012 (a), 2013 (b) and 2014 (c) and for the perennial cropping system in 2012 (d), 2013 (e) and 2014 (f). In 2013, the perennial cropping system was

cropped with canola. NLM–N-based liquid manure; PLM–P-based liquid manure; NSM–N-based solid manure; PSM–P-based solid manure. The error bars represent the standard deviation

with NLM at this study site in 2010 and 2011 (Karimi et al. 2018a).

Our findings show that increased nutrient availability caused by the conversion of PCS may not necessarily boost canola yields in this chernozemic

Table 5 Amount of annual leachate and flow weighted mean concentration (FWMC) and leached nitrate

Group means	Amount of leachate (mm)			FWMC NO ₃ -N (mg L ⁻¹)			Leached NO ₃ -N (kg ha ⁻¹)			
	2012	2013	2014	2012	2013	2014	2012	2013	2014	
<i>Crop × manure</i>										
<i>Annual</i>										
NLM ^a	0	141.0	98.0	–	54.3a	23.7	–	76.6	11.6	
PLM	0.5	216.8	109.0	1.5	29.3ab	21.4	–	63.6	11.7	
NSM	0	162.4	30.1	–	44.7ab	14.6	–	72.5	3.3	
PSM	0	233.4	73.4	–	23ab	8.8	–	53.6	6.8	
Control	0.6	177.7	32.5	2.0	19.8b	6.0	–	35.1	0.9	
<i>Perennial</i>										
NLM	12.6	162.7	21.8	8.6	12.6a	48.1	2.6	20.6	10.5	
PLM	41.1	200.1	48.3	2.6	15.2a	64.8	1.3	30.4	31.3	
NSM	0	177.0	19.6	–	12.8a	31.7	–	22.6	6.2	
PSM	17.4	170.9	57.4	0.7	12.8a	44.8	0.1	20.4	25.7	
Control	21.8	156.5	59.0	0.4	8.6b	12.2	0.1	3.2	7.2	
<i>Crop</i>										
Annual	0.2	186.3	47.7	1.8	38.2a	17.4b	–	60.3a	6.9b	
Perennial	18.6	173.4	41.2	3.1	11.0b	33.9a	0.8	19.4b	16.2a	
<i>Manure</i>										
NLM	6.3	151.9	43.6	8.6	37.1a	33.0a	1.3	48.6a	11.1	
PLM	20.8	208.5	32.0	2.1	23.2ab	33.4a	0.6	47.0a	21.5	
NSM	0	169.7	40.6	–	27.9a	19.4ab	–	47.5a	4.8	
PSM	8.7	202.2	65.4	0.7	22.7ab	30.4a	–	37.0ab	16.3	
Control	11.2	167.1	40.9	1.2	12.1b	8.9b	–	19.1b	4.0	
Model effect	df	<i>P</i> value ^b								
Crop	1	NA ^c	0.51	0.49	NA	< 0.001	0.10	NA	< 0.001	0.10
Manure	4	NA	0.58	0.83	NA	< 0.001	0.06	NA	0.01	0.23
Crop × manure	4	NA	0.90	0.57	NA	0.014	0.94	NA	0.51	0.67

^aACS Annual cropping system; PCS Perennial cropping system; NLM N-based liquid manure; PLM P-based liquid manure; NSM N-based solid manure; PSM- P-Based solid manure

^bMeans with different letters within the column and a cropping system are significantly different at $P < 0.1$ according to Tukey–Kramer test

^cStatistical analyses were not performed for 2012 leaching data due to insufficient samples

soil. Canola grown on the perennial plots showed greater average biomass and nutrient uptake than that grown on the ACS, possibly due to the better soil fertility from enhanced mineralization of accumulated soil organic matter (Adelekun et al. 2019). However, the greater biomass growth of canola on the former perennial plot did not translate into greater oilseed yields.

Our results show that P-based manure application favours less P demanding crops like canola on this Chernozem. The P-based treatments failed to produce consistent yields for barley and perennial grasses compared to the N-based systems. Barley is responsive to P fertilization, particularly during drought conditions (Jones et al. 2005). In contrast, canola oilseed yields are seldom affected by the lack of P fertilization (Belanger et al. 2015). This observation

could explain the different yield responses from the P-based manure treatments for barley and canola in our study. Treatment effects can also be affected by the type of crop. For example, the PLM treatment showed significantly greater corn grain yields when compared to PSM in a 7-year corn-soybean rotation (Hao et al. 2015). However, the soybean yields did not significantly differ between the two types of manure (Hao et al. 2015).

Although manure was applied to P-based treatments to satisfy the crop P requirement for 5 years, it appears that the P-based systems did suffer from insufficient P as indicated by smaller crop P uptake and Olsen P when compared to N-based treatments. The conversion of plant-available soil P into unavailable forms occurs with time (P ageing). The P-based treatments were also affected by the lack of N fertilization in 2014, as indicated by smaller crop N uptake on the P-based plots. An application of manure at a higher frequency than in the current study with regular urea-N in between manure application may help the P-based treatments produce yields in high P demanding crops such as barley and perennial grasses that are comparable to N-based treatment.

Soil available phosphorus increased over time in the N-based manure treatments

Our results indicate that the agronomic benefits of the N-based manure application (Greater biomass yields) could also come with negative environmental impacts (Increased Olsen P and $\text{NO}_3\text{-N}$ leaching). The Olsen P was consistently greater and gradually increased over time in the N-based treatments with a bigger increase with the NSM treatment. This finding was a deviation from the first three-year observation where the surface Olsen P content of the NSM and NLM treatments did not significantly differ (Karimi et al. 2018a). The N:P ratio of the solid swine manure is smaller than the liquid form (Karimi et al. 2018a), which resulted in greater P application in the NSM treatment than in the NLM treatment (Table S1). Replanting the former perennial plots to grasses in 2014 reduced P accumulation on the NLM treatment but not on the NSM treatment. The surface accumulation of P could potentially result in elevated surface P losses (Miller et al. 2011).

As expected, and consistent with other studies (Eghball and Power 1999; Karimi et al. 2018a;

Komiyama et al. 2014; Toth et al. 2006), the Olsen P was greater in the N-based manure treatments than in P-based systems in all seasons except in spring 2012. The increase in Olsen P on the ACS and PCS of the PSM treatments observed in 2014 could be due to the wetter and warmer conditions in 2013, coupled with the tillage of both cropping systems in that year, which led to increased mineralization and more P becoming available in the solid manure treated plots.

Continuous manure application was shown to result in substantial sub-surface P losses in clayey and loamy textured soils that are prone to preferential flow (King et al. 2015). However, the differences in the surface Olsen P concentration were not reflected in the subsurface P leaching at this study site. Coarse textured soils such as the sandy loam in this study often lack preferential flow paths and result in smaller subsurface P losses ($< 0.1 \text{ kg ha}^{-1}$). This is also supported by the fact that the Olsen P did not exceed 15 mg kg^{-1} below 30 cm depth in any manure treatments. However, the high P at 0.15–0.3 m in the N-based manure treatments in 2014 indicates a potential future buildup of subsurface P in the cropping systems that continuously receive N-based swine manure.

The N-based and liquid treatments are susceptible to nitrate leaching during wetter months

The FWM $\text{NO}_3\text{-N}$ concentration and $\text{NO}_3\text{-N}$ leaching loads were smaller from both cropping systems in 2012 due to drier conditions. Most of the $\text{NO}_3\text{-N}$ losses from the annual cropping system occurred in 2013, a wetter year with substantial spring precipitation. Manitoban soils are susceptible to elevated subsurface $\text{NO}_3\text{-N}$ losses in spring due to thawing of the subsurface soil-ice layer, timing of fertilization and occurrence of low-intensity, long-duration storms that favor downward water and nutrient movement (Nikiema et al. 2013; Kokulan et al. 2019, 2021b). In 2013, the FWM $\text{NO}_3\text{-N}$ concentration on the ACS was elevated for all manure treatments, including the control ($> 20 \text{ mg L}^{-1}$). High spring precipitation that coincided with fertilization might have exacerbated the subsurface $\text{NO}_3\text{-N}$ losses from the swine manure treated plots. Intense precipitation could have also flushed the unused nutrients in the dry year of 2012 (Dougherty et al. 2020). Significant $\text{NO}_3\text{-N}$ leaching losses from NSM, NLM and PLM treatments (relative

to the control) in 2013 in the ACS highlight the vulnerability of N-based and liquid manure application to $\text{NO}_3\text{-N}$ leaching during wetter months. It is possible that applied N was immobilized by the straw in the PSM treatment as speculated by Karimi et al (2017).

Conversion of perennial systems to annual systems elevated nitrate leaching losses

The seeding of the perennial plots to canola increased $\text{NO}_3\text{-N}$ leaching losses by a factor of 6 in the control plots and by a factor of 22 to 56 in the manured plots in 2013 compared to the previous 3-year average (2009–2011) (Karimi et al. 2017). The negative impacts of converting the perennial plots to annual plots on $\text{NO}_3\text{-N}$ leaching were further confirmed in 2014. Despite the re-introduction of perennial grasses, the FWM $\text{NO}_3\text{-N}$ concentration and leaching loads in 2014 were substantially elevated on the PCS (relative to 2013) and higher than the ACS. Conversion of a PCS into an ACS could mobilize N and P from relatively unavailable organic reserves through increased mineralization. Previous studies have shown increased $\text{NO}_3\text{-N}$ leaching losses following the conversion of perennial grasslands to annual cropping (Huggins et al. 2001) and vice-versa (Smith et al. 2013). The current study shows that converting a perennial system to annual cropping for shorter periods like a year could still have negative consequences beyond the conversion period.

Conclusions

The results of this study showed the potential of N-based manure applications to produce greater barley and perennial grasses yields than P-based applications. However, this comes with an environmental cost as N-based cropping systems increased soil available phosphorus and subsurface $\text{NO}_3\text{-N}$ leaching. Our results also demonstrated that the P-based manure treatments could significantly reduce the available phosphorus. There was also a reduction in $\text{NO}_3\text{-N}$ leaching from the P-based solid manure application in the annual cropping system. The P-based manure application favored less P-demanding crops like canola. However, additional P supplementation could be needed for increased barley and

perennial grasses yields. Future research should explore how P-based systems can be better managed for high P demanding crops with minimal environmental consequences. Finally, the current study also showed that converting a perennial cropping system to an annual cropping could substantially increase $\text{NO}_3\text{-N}$ leaching risk beyond the conversion period.

Acknowledgements The contribution of laboratory and field technicians and summer students in conducting this study is acknowledged and appreciated.

Data availability The data are available from the corresponding author, upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interests.

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