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ARTICLE

Nitrogen and phosphorus distribution in plant, soil, and leachate as affected by liquid hog manure and chemical fertilizers

Vivekananthan Kokulan, Mihiri C.W. Manimel Wadu, Olalekan O. Akinremi, and K.E. Buckley

Abstract: A 2 yr field study was conducted on a coarse-textured soil in Manitoba, Canada, to investigate the effects of liquid hog manure (LHM) and chemical fertilizer application on barley (2005) and red spring wheat (2006) yields, crop nutrient uptake, and nitrogen (N) and phosphorus (P) movement to the environment. The treatments were LHM applied at two rates as 22 000 L·ha^{-1} (2500 gal·ac^{-1}, abbreviated as M2500) and 43 000 L·ha^{-1} (5000 gal·ac^{-1}, abbreviated as M5000) and two rates of chemical fertilizer to match total N and P in LHM treatments, F2500 and F5000, along with an unamended control. The M5000 and M2500 treatments showed similar grain yield and N and P uptake. However, M5000 and M2500 significantly increased grain yield by 67% and 78%, respectively, compared with the control in 2005. In 2006, wheat grain yields from M2500 and M5000 were 71% and 86% greater than the control. In 2005, leachate NO_3-N concentrations and leaching loads were higher with chemical fertilizers than M2500. In 2005, the apparent recovery of applied N as leachate was 35% and 23% in F5000 and F2500 treatments, whereas it was 6% and 7% of applied N in M5000 and M2500 plots, respectively. However, the application of M5000 resulted in P accumulation near the surface and may increase the potential risk of P loss with runoff. Our results show that applying LHM at moderate rates (M2500) may ensure desirable crop yields comparable to higher rates of nutrient application with minimal potential losses relative to higher rates.

Key words: nitrate leaching, swine manure, nitrogen use efficiency, soil test phosphorus, crop phosphorus uptake.

Résumé : Les auteurs ont réalisé une étude sur le terrain de deux ans sur un sol à texture grossière du Manitoba (Canada) en vue d'approfondir les effets de l'application de lisier de porc (LP) et d'un engrais chimique sur le rendement de l'orge (2005) et du blé roux de printemps (2006), sur l'absorption des oligoéléments par la culture ainsi que sur les mouvements de l'azote (N) et du phosphore (P) dans l'environnement. Les traitements étaient les suivants : application de LP à raison de 22 000 litres par hectare (2500 gallons par acre, M2500) ou de 43 000 litres par hectare (5000 gallons par acre, M5000) et application d'un engrais chimique en quantité suffisante pour parvenir à la même concentration totale de N et de P qu'avec le LP (F2500 et F5000). L'étude incluait une parcelle témoin non bonifiée. Les traitements M5000 et M2500 ont donné lieu à des résultats similaires pour le rendement grainier et l'absorption du N et du P. Toutefois, en 2005, ces traitements ont sensiblement accru le rendement grainier comparativement à celui relevé sur la parcelle témoin, soit respectivement de 67 % et de 78 %. En 2006, le rendement grainier du blé obtenu avec les traitements M2500 et M5000 dépassait celui de la parcelle témoin de 71 % et de 86 %, respectivement. En 2005, la quantité de N-NO_3 perdue et l'importance de la lixiviation étaient plus élevées avec l'engrais chimique qu'avec le traitement M2500. En 2005, la part apparente de N récupérée dans le lixiviat s'établissait respectivement à 35 % pour le traitement F5000 et à 23 % pour le traitement F2500, contre 6 % pour les parcelles M5000 et 7 % pour les parcelles M2500. Le traitement M5000 a néanomois entraîné une accumulation de P près de la surface, ce qui pourrait accroître le risque d'une lixiviation de cet élément lors du ruissellement. Les résultats de l'étude indiquent que l'application d'une quantité modérée de LP (M2500) garantirait un rendement comparable à celui obtenu avec l'application d'une quantité supérieure d'oligoéléments tout en minimisant les pertes potentielles associées à un taux d'application plus élevé. [Traduit par la Rédaction]

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Mots-clés : lixiviation du nitrate, fumier de porc, efficacité de l'utilisation de l'azote, dosage du phosphore dans le sol, assimilation du phosphore par la culture.

Introduction

Most nutrients are applied to croplands, either as chemical fertilizers or manure. Liquid hog manure (LHM) is a source of mineral nitrogen (N) and phosphorus (P), and it is an efficient fertilizer for crop production (Wilson et al. 2010). In Canada, the province of Manitoba is the largest contributor to Canadian pork production (30% in 2015) (Honey 2016). In 2007, hogs in Manitoba excreted around 22 000–24 000 Mg of N and 5000–7000 Mg of P, and a substantial portion of this manure was applied to croplands (Brewin et al. 2007). However, overapplication of LHM may increase the risk of surface and groundwater pollution due to elevated runoff and leaching-related nutrient losses. Pollution of surface and groundwater bodies is a global and Canadian environmental problem (Padilla et al. 2018; Le Moal et al. 2019). Agricultural runoff and nutrient leaching play a critical role in transporting nutrients from the farms to surface and groundwater reserves. There is a need to manage livestock manure and chemical fertilizer applications to minimize pollution in Lake Winnipeg and associated groundwater reserves (Schindler et al. 2012).

A substantial proportion of N and P in LHM is readily available for plant uptake (Sánchez and González 2005; Karimi and Akinremi 2018). However, this readily available proportion of N and P in LHM varies depending on manure management such as storage and dilution (Conn et al. 2007). Variability in nutrient contents of manures makes applying precise and accurate amounts of nutrients more complicated, requiring constant laboratory testing. Therefore, a proper understanding of plant P and N uptake from manure and fertilizer applied at similar rates is needed to evaluate the effectiveness of LHM for crop production relative to that of chemical fertilizers.

Several studies have assessed the impacts of LHM on runoff, leaching, and crop performance to understand the role of LHM as a nutrient source to crops and as a source for nutrient pollution of water bodies. In general, increased LHM application rates were associated with increased yields of wheat and corn (Nikiéma et al. 2013; Thilakarathna et al. 2015). Elsewhere, greater crop yields were reported with LHM application when compared with similar chemical fertilizer N application rates (e.g., Mooleki et al. 2002; Meade et al. 2011). However, the yield advantage of LHM was not observed in coarse-textured soils of Manitoba when compared with similar chemical fertilizer rates (Buckley et al. 2011; Karimi and Akinremi 2018). Therefore, further investigation is required on how fertilizer and LHM applications could affect biomass and nutrient uptake and partitioning (e.g., nutrients in straw versus grain) in field crops on coarse-textured Manitoba soils that are vulnerable to nitrate leaching.

Application of LHM based on plant N requirement rates could significantly increase P losses through surface runoff pathways by elevating soil test P in the upper soil profile (Royer et al. 2003; Kumaragamage et al. 2011; Karimi et al. 2018). Even though the risk of P leaching through the soil matrix is low when compared with N, P could still reach the groundwater and subsurface tile drains through preferential flow pathways (King et al. 2015). Greater LHM application rates could increase surface runoff-related NO_3^- losses by increasing the NO_3-N content at the soil surface (King et al. 2017). In contrast, greater LHM application rates could also increase the NO_3-N leaching potential, especially in coarse-textured soils (Nikiéma et al. 2013). However, this leaching potential of LHM is found to be lower when compared with similar rates of chemical fertilizers (Kumaragamage et al. 2012; Karimi and Akinremi 2018). Several studies have shown that applying LHM in lower to moderate N rates could provide better utilization of N while minimizing the environmental risk (Mooleki et al. 2002; Nikiéma et al. 2013). However, studies that assessed crop performances and N and P leaching losses from LHM and fertilizer applications are lacking.

Determination of nutrient leaching out of the root zone is challenging. Soil samples taken within the soil profile may not be accurate in inferring the magnitude of nutrient leaching from the root zone due to the variability in microtopography and soil physical characteristics (Olatuyi et al. 2012; Kokulan et al. 2018). Uncertainties could arise when a continuous process such as leaching is measured using soil samples collected from different locations at different time scales. Therefore, direct measurements of nutrient leaching from intact field core lysimeters may provide better information on the comparative magnitude of nutrient loss from manure and fertilizer.

Previous studies from the Prairie region have shown that LHM application at moderate rates could improve crop yields with minimal NO_3-N leaching (Nikiéma et al. 2013). Research from this region has also shown that LHM application at moderate rates could improve crop yields with minimal NO_3-N leaching when compared with similar rates of chemical fertilizers (Karimi and Akinremi 2018). However, subsurface tile drainage systems are expanding on the Canadian Prairies (Kokulan et al. 2019), and P has the potential to reach subsurface drainage systems through preferential flow pathways (King et al. 2015). Research from other regions and soil types has shown that LHM might increase surface and subsurface phosphorus losses over inorganic fertilizers and other animal manure sources (Hodgkinson et al. 2002;

Kinley et al. 2007). Manure- and chemical-fertilizer-related surface and subsurface P losses have been assessed on the Canadian Prairies (King et al. 2017; Karimi et al. 2018; Kokulan et al. 2019). However, studies that examined crop utilization and leaching potential of N and P from LHM in comparison to chemical fertilizers are rare. This study aimed to fill this gap by simultaneously assessing the plant utilization and leaching potential of N and P in the LHM in comparison to similar chemical fertilizer application rates.

Based on the literature, we hypothesized that the application of LHM would not significantly affect crop yields when compared with similar rates of inorganic fertilizer but would substantially increase P loss risk via surface and subsurface pathways. We also hypothesized that the application of inorganic fertilizers would pose a higher risk of subsurface NO_3-N leaching. Therefore, the specific objectives of this study were (*i*) to compare the effect of LHM and chemical fertilizers on crop yields and crop uptake of N and P, (*ii*) to assess the N and P leaching potential of LHM and compare it with chemical fertilizers, and (*iii*) to recommend an agronomically and environmentally sound fertilization strategy for a coarse-textured soil.

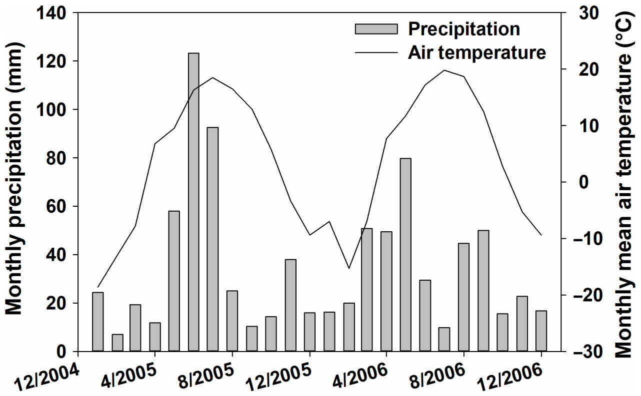
Materials and Methods

Field design and treatment application

The experiment was conducted on a cooperator field, located northwest of the town of Carberry in southwestern Manitoba, Canada (latitude 49°53′59″N, longitude 99°20′59″W). This study site is located over the Assiniboine Delta Aquifer, an unconfined aquifer that is the source of water for people in this rural region of Manitoba. The field study was conducted during two consecutive years (2005 and 2006) on a well-drained Orthic Black Chernozem soil. The texture of the upper 90 cm soil is classified as sandy loam, whereas the underlying material (90–120 cm depth) being loam (Kokulan et al. 2018). The mean cumulative annual precipitation for the 1996–2006 period in this region was 502 mm, whereas the mean monthly temperature was 2.5 °C (Environment and Climate Change Canada 2014). The monthly precipitation and monthly mean air temperature for the experimental period (2005–2006) are given in Fig. 1.

The field experiment was a randomized complete block design with six treatments and four replicates for a total of 24 experiment units, each of which measured 10 m × 10 m. The treatments were randomized within four blocks in a relatively flat field measuring 65 m × 55 m (0.36 ha), and blocks were separated by 5 m buffer zones. The treatments included a control (no nutrients added), two rates of LHM application, and two chemical fertilizer treatments that matched the total N and P contents in each LHM treatment. The sixth treatment was a beef manure compost that was used as a P source with urea added to provide N at the same rate as the lower rate of fertilizer or LHM. However, the beef manure compost treatment was excluded from this paper to emphasize the effects of LHM and chemical fertilizer treatments on soil and crop performance. The desired rates for manure application were 2500 and 5000 gal·ac^{-1} (22 000 and 43 000 L·ha^{-1}) to match single and double passes of the AerWay manure applicator. The low-manure application rate will be denoted as M2500, whereas the high-manure application rate will be denoted as M5000, hereafter. The equivalent chemical fertilizer treatments will be denoted as F2500 and F5000, respectively. Chemical analyses of manure are described in the "data collection and analyses" section. The results of the LHM analysis showed that the low- and high-manure treatments approximate total N application rates of 94 and 189 kg N·ha^{-1} in 2005 and 21 and 42 kg N·ha^{-1} in 2006. Total P was applied at rates of 30 and 15 kg P·ha^{-1} in 2005 and 10 and 5 kg P·ha^{-1} in 2006 in high- and low-manure application rates, respectively. The manure applied in 2006 had lower N and P content (Table 1). The chemical fertilizer treatments were prepared by mixing urea and monoammonium phosphate to match the total N and P that was in each manure treatment in both years of the study. The control, M2500, M5000, and F5000 plots received similar treatments from 2002 (Enns 2004). The study began in 2002 with two F5000 treatments. One was cropped, and the other was left fallow to provide an extreme soil hydrological condition for leaching. Starting from 2005, the fallow treatment was discontinued and converted to F2500 that received N and P applications to match the total N and P of M2500.

Fig. 1. Monthly precipitation and mean air temperature during 2005 and 2006 experimental period. Weather data were obtained from the Historical weather archive (Environment and Climate Change Canada 2014).



All plots except the F2500 had been cropped to hard red spring wheat (*Triticum aestivum* L. 'AC Barrie') for three consecutive years before 2005 (Nikiéma et al. 2013). Before seeding in 2005 and 2006, plots were tilled to about 10 cm soil depth with a rototiller. The treatments were surface applied once a year, using an

Table 1. Chemical composition of the hog manure applied to the plots in 2005 and 2006.

Year	Moisture content (%)	EC ($ds{\cdot}m^{-1}$)	pH	Total N (%)	NO_3^- ($mg{\cdot}L^{-1}$)	NH_4^+ ($mg{\cdot}L^{-1}$)	Ca (%)	P (%)	K (%)	Mg (%)	Na (%)	S (%)
2005	98.9	15.6	7.6	0.2	1.0	2030	0.03	0.03	0.13	0.01	0.03	0.02
2006	99.2	NA	NA	0.08	0.5	648	NA	0.01	NA	NA	NA	NA

Note: EC, electrical conductivity, N, nitrogen; Ca, calcium, P, phosphorus, K, potassium; Mg, magnesium, Na, sodium; S, sulfur; NA, not available.

AerWay manure application system. Tilling and treatment applications were done manually within the lysimeters with a garden fork to mimic field operation. Treatments were applied on 25 May in 2005 and 26 May in 2006. Plots and lysimeters were seeded to barley on 31 May 2005, and with wheat on 31 May 2006. Chemical fertilizer application was made by broadcasting each year on the same day that the seeding was done. The plots were seeded at a rate of 120 $kg{\cdot}ha^{-1}$ (two bushels per acre).

The lysimeter design and installation are given in detail elsewhere (Enns 2004; Nikiéma et al. 2013). Large intact soil core lysimeters were installed in the experimental site in 2002 to collect percolated water below the rooting zone. Each lysimeter is made up of schedule 80 polyvinyl chloride pipe (3.3 cm thick, 54.2 cm i.d., and 106.7 cm deep) and was installed approximately in the middle of the plot. Each lysimeter consisted of a central column, a perforated plate to hold the soil and allow leachate to drain and a bottom cap to serve as a catch basin. Two drain pipes (0.64 cm in diameter) were attached to the bottom cap; one of the pipes was used for leachate removal by suction, and the second pipe served as a pressure equalizer during the leachate collection (Nikiéma et al. 2013). In 2005 and 2006, the lysimeters received the same treatments and agronomic practices as the plot within which they were installed.

Data collection and analysis

The chemical composition of manure was determined by analyzing representative manure samples (Table 1). Manure samples were taken from the storage tank a day before manure application. Total N and P of manure were analyzed using a modification of the wet oxidation method (Akinremi et al. 2003). Briefly, 40 mL of liquid manure was digested with 2.2 mL of digestion solution (H_2O_2, Se, and Li_2SO_4). The digested sample was analyzed for NH_4-N using a Technicon auto-analyzer (Maynard and Kalra 1993). Total P was colorimetrically determined with the molybdate-blue method (Murphy and Riley 1962) by using an Ultrospec 3100 pro UV/Visible Spectrophotometer (Biochron Ltd., Cambridge, UK).

Plant biomass samples were taken manually on 31 Aug. in 2005 from two randomly placed 1 m × 1 m quadrants and on 24 Aug. in 2006 from four randomly placed 1 m × 1 m quadrants in each plot. Biomass samples taken from each plot were combined into a single bag in each year. Air-drying was carried out inside a drying room (with warm, dry airflow at 32 °C) to allow the plant samples to dry for at least 2 wk period. Experience has shown over the years that the drying room accomplished dry mass comparable to a hot air oven. The grain was then threshed, and the grain and straw were subsampled and finely ground with a mini-ball mill for chemical analyses. Plant analysis was conducted using the wet oxidation method (Parkinson and Allen 1975) using a 0.4 g sample of ground plant material. The digested solution was analyzed for total N by the cadmium reduction procedure, using a Technicon Auto Analyzer II (Maynard and Kalra 1993), and total P was determined according to molybdate-blue method (Murphy and Riley 1962). Plant N uptake and plant N use efficiency (NUE) were estimated from the concentration of total N in plant samples, dry matter yield, and total N applied ($kg\ N{\cdot}ha^{-1}$) as inorganic or organic N source (Mooleki et al. 2002; Nikiéma et al. 2013). The NUE was calculated from

$$\mathrm{NUE} = \frac{\mathrm{Nup} - \mathrm{Ncon}}{\mathrm{Napp}}$$

where Nup is the crop N uptake from an amendment, Ncon is the crop N uptake from control, and Napp is the total N applied in the amendment.

Leachate collection from the lysimeters was performed using a vacuum pump and a 500 mL Erlenmeyer flask. Leachate samples collected were transferred into 10 L plastic containers and stored in a cooler with ice packs for transport from the field to the laboratory. The total volume of each leachate sample was then measured, and a subsample was stored at −20 °C until they could be analyzed (less than 1 wk). Leachates were collected after snowmelt in the spring and following significant rainfall events. In 2005, leachate collection commenced on 5 May, and subsequent leachate collections occurred on 6 June, 16 June, 23 June, and 17 July. Leachate sampling was conducted on 3 May, 18 May, 12 June, 23 June, and 7 July in 2006. A subsample per treatment from each leachate sampling event was analyzed for NO_3^--N (colorimetrically).

Soil samples were collected from the plots after harvest to determine residual N and P in soil. Soil sampling was conducted on 12 Oct. 2005 and 28 Sept. 2006 in 5 cm steel tubes using a Giddings soil sampler (Giddings Machine Co., Fort Collins, CO, USA). All soil samplings were performed by randomly taking two core holes within the plot, at the soil depth intervals of 0–10, 10–20, 20–30, 30–60, 60–90, and 90–120 cm. The two sample cores were composited, and a subsample (~10 g) was taken to determine gravimetric moisture content by the thermogravimetric method (Gardner 1986). All soil samples were analyzed for NO_3^--N and Mehlich-3 P. Nitrate-nitrogen was extracted using 2 $mol{\cdot}L^{-1}$ KCl at a soil:extractant ratio of 1:5 (Maynard and Karla 1993). The KCl extracts were analyzed colorimetrically using a Technicon auto analyzer II (Pulse Instrumentation Ltd., Saskatoon, SK, Canada). For Mehlich-3 P, the soil was extracted using a Mehlich solution at a soil:solution ratio of 1:10 (Mehlich 1984). Concentrations of P were determined colorimetrically using the molybdate-blue method (Murphy and Riley 1962). The mean residual NO_3-N concentrations for the top 10 cm soil prior to the treatment application in 2005 were 7.7, 8.9, 9.2, 8.5, and 9.4 $mg{\cdot}kg^{-1}$ for the control, M2500, M5000, F2500, and F5000 plots, respectively. The initial top 10 cm Mehlich-3 P concentrations for the control, M2500, M5000, F2500, and F5000 were 11.4, 20.8, 20.6, 13.3, and 24.75 $mg{\cdot}kg^{-1}$, respectively.

Statistical analysis of data

The plant, soil, and leachate data for each year were analyzed separately. The PROC MIXED procedure of SAS version 9.2 (SAS Institute Inc. 2008, University Edition) was used to assess the treatment effects on the aboveground biomass, straw and grain yields, N and P uptake, NO_3-N leaching, and soil residual NO_3-N and soil test P at 0–10 cm depth. Block (four levels) was included as a random factor in the model, whereas the treatment (five levels, including control) was considered as a fixed factor. PROC MIXED procedure was also used to assess the effects of treatments, depth, and interaction between treatments and depth. However, amendment and application rates were considered as separate fixed effects. Depth was treated as a repeated measure when soil N and P were analyzed. The spatial power covariance structure was used in the model for the repeated measures data in which the depth intervals were unequal (Nikiéma et al. 2013). The assumption of normal distribution was checked using PROC UNIVARIATE in SAS software (version 9.2). Plant variables were found to be normally distributed, whereas soil P and N data were log-transformed prior to analysis to meet the assumption of normality (Shapiro–Wilk's test). Treatment effects were compared with each other using the Tukey–Kramer's mean separation method at $p < 0.1$ significance level. This lower level of significance ($p < 0.1$) was used due to the high level of variability, which is typical for field leaching studies (Constantin et al. 2010; Ghiberto et al. 2015; Karimi and Akinremi 2018).

Results and Discussion

Climatic conditions

When compared with the previous 10 yr average, 2005 and 2006 study years were 12% and 19% dryer, respectively (Fig. 1). However, substantial differences in precipitation were observed during the crop growing period (June to August). For example, June to August period recorded 241 mm of precipitation in 2005 against the previous 10 yr average of 220 mm. However, precipitation in 2006 for this period was merely 84 mm. In addition, the year 2006 was warmer (3.9 °C) when compared with the previous 10 yr average (2.5 °C).

Plant biomass and grain yield

There was a significant treatment effect on grain yields in 2005 and 2006 (Table 2). Both manure treatments (M2500 and M5000) produced significantly greater grain yields than control treatments in 2005 and 2006 (Fig. 2). No significant yield advantage was observed for M5000 over M2500 treatment, despite receiving twice the amount of nutrients. All treatments increased the grain yield of barley above that of the control in 2005 (Fig. 2*a*). A grain yield of approximately 4.2 $Mg{\cdot}ha^{-1}$ was produced by M2500, F2500, and M5000 treatments in 2005.

Only F5000, M2500, and M5000 produced significantly greater wheat grain yields in 2006 when compared with control (Fig. 2*b*). Wheat grain yields from M2500 were significantly greater than from F2500 in 2006. Similarly, M5000 produced greater grain yields when compared with F5000. The greatest wheat yield in 2006 was approximately 1 $Mg{\cdot}ha^{-1}$ from both M2500 and M5000 LHM applications. However, this wheat yield from the experimental site was smaller than the average of 2.9 $Mg{\cdot}ha^{-1}$ recorded for Manitoba in 2006 (Government of Manitoba 2012). Smaller yields in 2006 could be due to the smaller amount of applied N and P and reduced precipitation at the Carberry site during the growing season. Although manure application rates were the same in both years and were added on a volume basis, total N and P in manure were almost four and three times greater in 2005 than 2006 (Table 1).

In 2005, all LHM and chemical fertilizer treatments produced significantly greater aboveground biomass when compared with control. However, both LHM treatments produced greater aboveground biomass in 2006 when compared with control and chemical fertilizers. In 2005, 40%–50% of the aboveground plant biomass was composed of grain, whereas it decreased to 32%–39% in 2006 (Fig. 2). Drier conditions that prevailed in the 2006 crop growing period could be the reason for the reduced amount of grain formation as crop response to added N is limited without adequate moisture (Wang et al. 2012). In general, greater precipitation during the growing season is positively related to greater crop yields (Hussain and Mudasser 2007). Previous studies conducted in this region have also recorded greater crop yields in years associated with regular or above-normal

Table 2. Significance of the effect of liquid swine manure and chemical fertilizers based on one-way analysis of variance.

			2005		2006	
		df	*f* value	*p* value	*f* value	*p* value
Yield	Grain	4	7	<0.01	11	<0.001
	Straw	4	16	<0.001	10	<0.001
	Aboveground biomass	4	12	<0.001	13	<0.001
N uptake	Grain	4	7	<0.01	8	<0.01
	Straw	4	11	<0.001	8	<0.01
	Aboveground biomass	4	10	<0.001	11	<0.001
P uptake	Grain	4	6	<0.01	2	NS
	Straw	4	7	<0.01	1	NS
	Aboveground biomass	4	9	<0.01	2	NS
NUE		3	2	NS	5	<0.05
Percolated water		4	3	<0.1	2	NS
FWMC nitrate		4	4	<0.05	2	NS
Leached nitrate loads		4	6	<0.01	1	NS

Note: NS, not significant at $p < 0.1$; NUE, nitrogen use efficiency; FWMC, flow weighted mean concentration.

growing season precipitation (Nikièma et al. 2013; Karimi and Akinremi 2018). Chemical fertilizer and LHM treatments also significantly increased the straw weights in 2005 compared with the control (Fig. 2). In contrast, both LHM treatments significantly increased the straw yields in 2006 when compared with the control and chemical fertilizers.

Our results show that chemical fertilizers did not outperform the LHM treatments with respect to grain, straw, and aboveground biomass yields. In fact, greater grain yield, straw, and aboveground total plant biomass were observed in the LHM treatments when compared with their corresponding chemical fertilizer treatments in 2006. A small crop yield advantage of LHM treatments was also reported from another study conducted in the region using barley and red spring wheat crops (Karimi and Akinremi 2018). The yield advantage in manure-amended plots over chemical fertilizer could be due to the other plant essential nutrients provided with manure that increased the soil nutrient status (Mooleki et al. 2002). Although the amounts of readily available N fractions are smaller in manures than in chemical fertilizers (Beauchamp et al. 1982; Jokela, 1992), the overall fertility of the soil could be enhanced by manure application. For example, LHM addition has been reported to positively affect enzyme activity, microbial biomass, and the N mineralizing bacteria population as compared with chemical fertilizer (Lalande et al. 2000). These microbial parameters, which are enhanced by the LHM, are known to increase crop yield.

Plant nitrogen uptake and NUE

A significant treatment effect on grain N uptake was observed in 2005 and 2006 (Table 2). The grain N uptake was in the range of 16–26 kg N·ha^{-1} in 2006, whereas it was 76–80 kg N·ha^{-1} in 2005 in the amended plots (Fig. 3). In both years, F5000, M2500, and M5000 treatments showed significantly greater grain N uptake when compared with control. Increasing N application rate generally results in increased N uptake in plants when applied in low to moderate amounts (Vasconcelos et al. 1997; Wang et al. 2012). However, the relationship between rate and N uptake is nonlinear. For example, Nikièma et al. (2013) saw a significant increase in N uptake between their high (192 kg N·ha^{-1}) and low (64 kg N·ha^{-1}) manure treatments. However, there were no significant differences between the high and medium rates (128 kg N·ha^{-1}) of LHM. In the present study, both M2500 and M5000 treatments had similar grain N uptake in both years. Observations from our study and other studies in this region suggest that greater LHM application may not result in increased grain N uptake (when compared with moderate rates) on this coarse-textured soil. This may be due to the limited water-holding capacity of this sandy soil.

A significant treatment effect was not observed for NUE of barley in 2005. In 2005, the NUE in barley was 61% with F2500 and 62% with M2500, whereas it was 40% for M5000 (Fig. 4). Other studies have also reported smaller NUE values for pig slurry applied at high rates in coarse-textured soils (Baral et al. 2017). However, M2500 had a greater NUE (80%) for wheat in 2006 over other treatments. Similar grain N removals (when compared with M5000) and greater NUE values (>60%) of M2500 treatment shows the efficiency of this treatment to utilize the applied N. However, this cannot be said for F2500 due to its smaller grain N removals (when compared with F5000) and smaller NUE values (<50%) in 2006.

Fig. 2. Grain yield, straw, and aboveground biomass with chemical fertilizer and liquid hog manure in 2005 (*a*) and 2006 (*b*). The abbreviations M2500 and M5000 denote liquid hog manure application rates at 2500 and 5000 gal·ac^{-1}, respectively, whereas F2500 and F5000 denote chemical fertilizer application rates that provided total N and P in M2500 and M5000 treatments, respectively. Error bars indicate standard deviation. Bars followed by the same letter are not significantly different at $p < 0.1$.

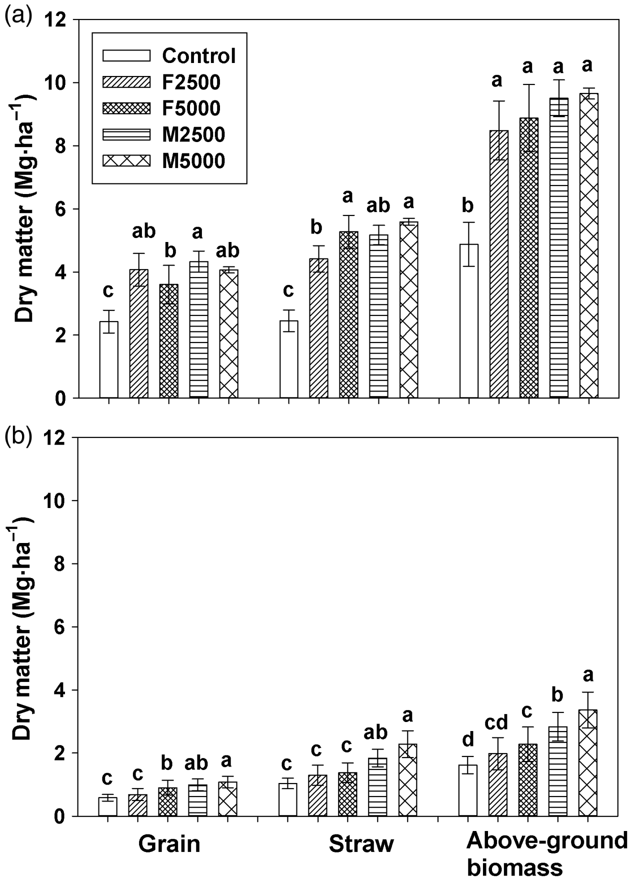
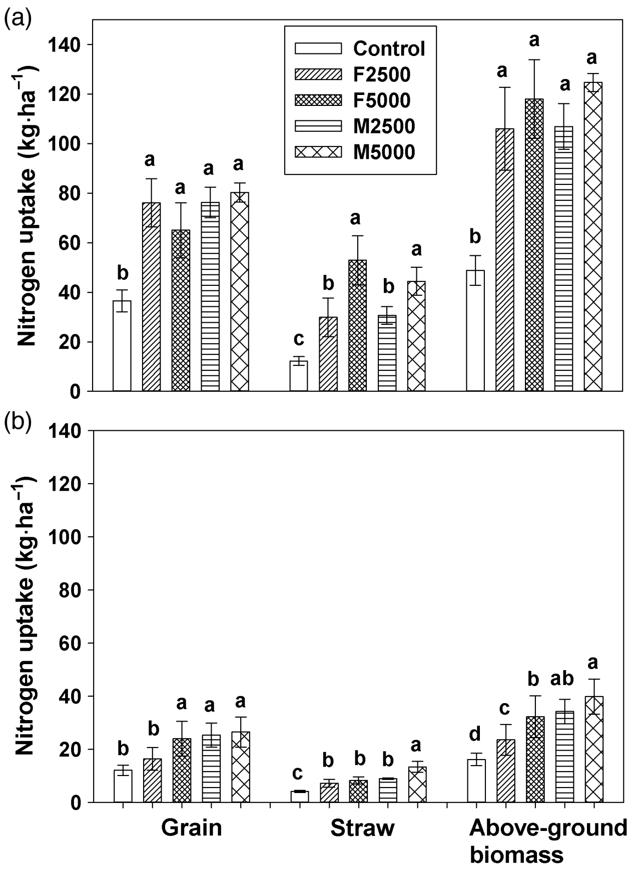


Fig. 3. Total nitrogen (N) uptake and N uptake in grain, straw, and aboveground biomass with chemical fertilizer and liquid hog manure in 2005 (*a*) and 2006 (*b*). The abbreviations M2500 and M5000 denote liquid hog manure application rates at 2500 and 5000 gal·ac^{-1}, respectively, whereas F2500 and F5000 denote chemical fertilizer application rates that provided total N and P in M2500 and M5000 treatments, respectively. Error bars indicate standard deviation. Bars followed by the same letter are not significantly different at $p < 0.1$.



Plant phosphorus uptake

The treatments also affected the P uptake by the grains, straw, and the aboveground biomass (Table 2). In contrast, there was no treatment effect on P uptake in 2006. Consistent with the N uptake, P uptake was also smaller in 2006 compared with 2005, potentially due to the drier condition and low P application rate in 2006 (Fig. 5). In 2005, the two rates of manure had significantly greater grain P uptake than the control treatment (Fig. 5). In 2005, F2500 treatment had greater grain P uptake when compared with control and F5000. However, this was not observed in 2006. Greater microbial activity in soils treated with manure increases P availability to plants when compared with inorganic fertilizer treatments (Ebeling et al. 2003; Barbazán et al. 2009). However, this advantage was likely to be affected by drier conditions, limited P supply, and poor crop growth in 2006.

Nitrogen leaching losses

The data reported below were from the analysis of the yearly cumulative leachate volume and leached NO_3-N. Spatial and temporal variability of leaching events precluded the analysis of data from individual leaching events. In 2005, flow-weighted mean NO_3-N concentration ($p < 0.05$) and NO_3-N leaching loads ($p < 0.01$) were significantly affected by the treatments (Table 2). However, the treatment effect on NO_3-N concentration and NO_3-N leaching loads was not observed in 2006, probably due to lower leachate volumes (Fig. 6). The amount of percolated water and leached NO_3-N was substantially greater in 2005 than in 2006, due to the greater precipitation during the growing period (June to August) and greater N application rates in 2005 (Fig. 6). In 2005, water percolation was significantly smaller under the M5000 treatment when compared with control. The flow-weighted mean NO_3-N

Table 3. Flow weighted mean NO_3-N concentrations (mg N·L^{-1}) of the cumulative leachate collected by the lysimeters ($n = 4$ per treatment) in 2005 and 2006.

Year		Control	F2500	F5000	M2500	M5000
2005	Minimum	1.6	23.4	94.8	5.3	0
	Mean	7.68b	110.5a	153.3a	24.3b	32.8ab
	Maximum	15.7	198.9	293.3	49.4	52.8
2006	Minimum	0.5	13.7	0	0	0
	Mean	6	76.4	51.4	7.9	10
	Maximum	16	177.2	180.7	22.3	23.3

Note: Means with the same lowercase letters are not significantly different at $p < 0.1$.

Fig. 4. Nitrogen use efficiency of barley (2005) and wheat (2006) with chemical fertilizer and liquid hog manure. The abbreviations M2500 and M5000 denote liquid hog manure application rates at 2500 and 5000 gal·ac^{-1}, respectively, whereas F2500 and F5000 denote chemical fertilizer application rates that provided total N and P in M2500 and M5000 treatments, respectively. Error bars indicate standard deviation. Bars followed by the same letter are not significantly different at $p < 0.1$.

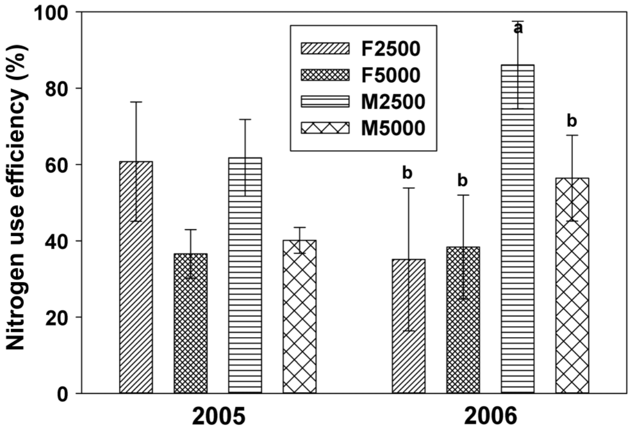
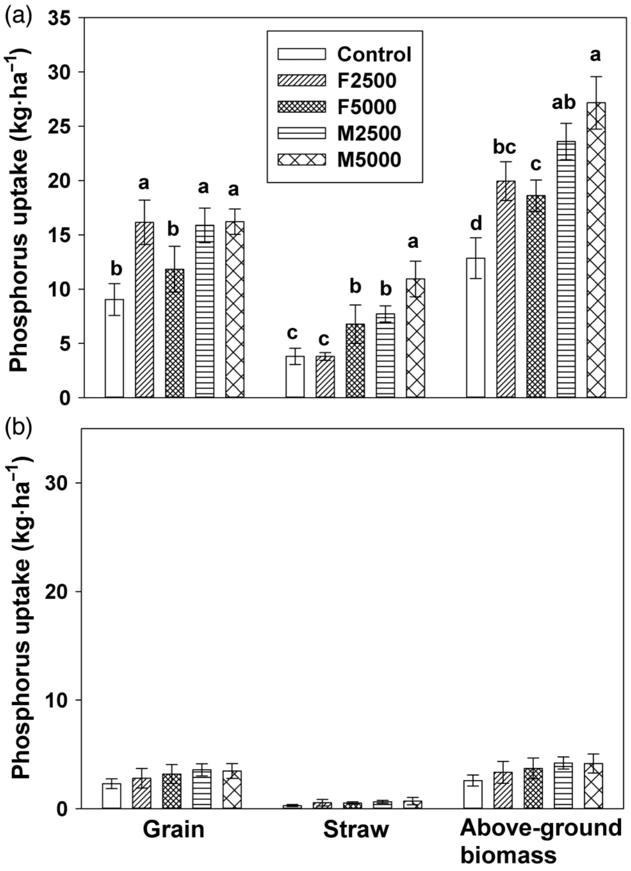


Fig. 5. Total phosphorus (P) uptake and P uptake in grain, straw, and aboveground biomass with chemical fertilizer and liquid hog manure in 2005 (*a*) and 2006 (*b*). The abbreviations M2500 and M5000 denote liquid hog manure application rates at 2500 and 5000 gal·ac^{-1}, respectively, whereas F2500 and F5000 denote chemical fertilizer application rates that provided total N and P in M2500 and M5000 treatments, respectively. Error bars indicate standard deviation. Bars followed by the same letter are not significantly different at $p < 0.1$.



concentration under M5000 and M2500 treatments were statistically similar and were not significantly different from the control treatment (Table 3). The FWM NO_3-N concentration under the M2500 treatment was also smaller than the F2500 and F5000 treatments in 2005.

In general, water and leachate volumes and NO_3-N concentration collected under the same treatment showed considerable variability. Significant spatial variability in soil texture and soil water content were reported at this study site (Kokulan et al. 2018). This variability might have influenced the leached water and NO_3-N within the lysimeters (Vivekananthan 2014).

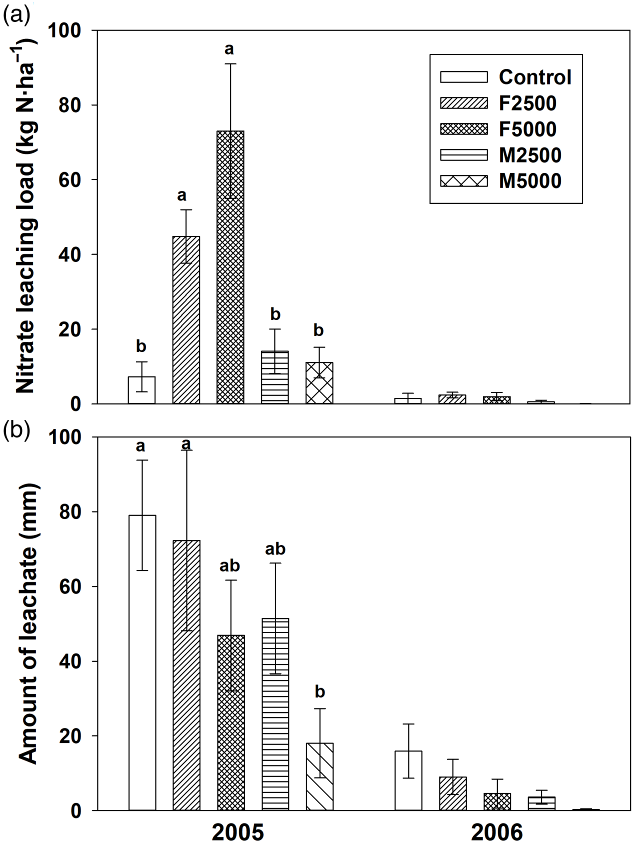
The control treatment produced significantly greater amounts of leachate in 2005 when compared with the M5000 treatment (Fig. 6*b*). In contrast, all grain, straw, and aboveground biomass were significantly greater for M5000 in both years when compared with control treatment (Fig. 2). Smaller percolation from the M5000 treatment could be due to better crop yield, and biomass production relative to control treatment (Campbell et al. 1993; Olatuyi et al. 2012). However, the FWM NO_3-N concentration of all treatments except the control

Table 4. Analysis of variance results showing the liquid swine manure and chemical fertilizer treatment and rate effects on residual soil NO_3-N (0–120 cm) and soil test phosphorus (P) (0–10 cm) in 2005 and 2006.

	p value			
	2005		2006	
Effect	NO_3-N	P	NO_3-N	P
Amendment	**0.018**	**0.007**	0.375	0.665
Rate	**0.028**	**0.014**	**0.018**	0.263
Amendment × rate	0.613	**0.059**	0.391	0.145
Depth	**<0.0001**	—	**<0.0001**	—
Amendment × depth	0.904	—	0.662	—
Rate × depth	0.951	—	**0.062**	—
Amendment × rate × depth	0.822	—	0.982	—

Note: Bold-face type indicates treatments that are statistically significant at $p < 0.1$.

Fig. 6. Nitrate leaching load (*a*) and amount of leachate collected below the 120 cm depth by the lysimeters (*b*). The abbreviations M2500 and M5000 denote liquid hog manure application rates at 2500 and 5000 gal·ac^{-1}, respectively, whereas F2500 and F5000 denote chemical fertilizer application rates that provided total N and P in M2500 and M5000 treatments, respectively. Error bars indicate standard deviation. Bars followed by the same letter are not significantly different at $p < 0.1$.



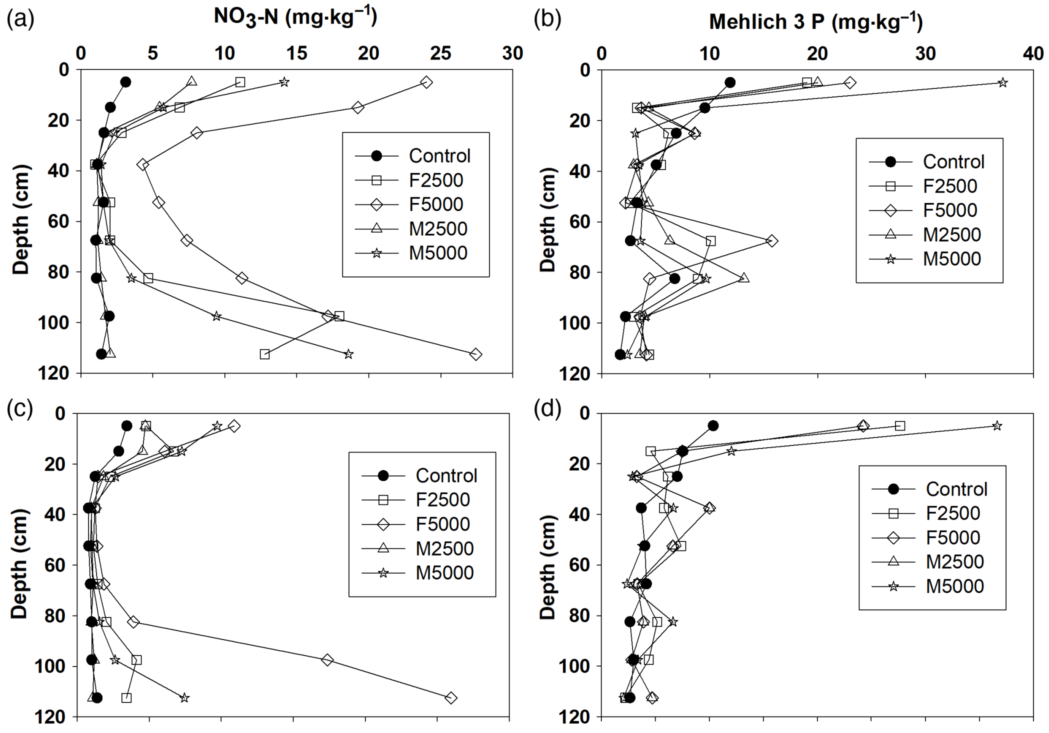
exceeded the recommended guidelines for the maximum acceptable concentration of 10 mg N·L^{-1} in drinking water in 2005 (Olsen et al. 2009), whereas mean FMW NO_3-N concentration for LHM treatments and control were equal to or below 10 mg N·L^{-1} in 2006.

The total NO_3-N leaching load was greater in the plots treated with chemical fertilizer compared with LHM in 2005 (Fig. 6). Leaching losses were generally smaller in 2006, due to smaller N application rates and smaller leaching volumes. On average, the total NO_3-N load in leachate collected from the plots treated with F5000 was 67 kg·ha^{-1} in 2005, whereas it was 4 kg·ha^{-1} in 2006. The F2500 treatment resulted in 45 and 2.4 kg N·ha^{-1} in the leachate in 2005 and 2006, respectively. When compared with the amount of N applied as chemical fertilizers in 2005, 35% and 23% of N was leached with the percolated water in F5000 and F2500 treatments, respectively. In contrast, NO_3-N leaching loss was 6% and 7% in 2005 with M5000 and M2500 treatments, respectively. These results are consistent with those of Karimi and Akinremi (2018), who reported greater NO_3-N losses under chemical fertilizer application. Our results showed that in 2005, approximately 3–6 times more N was leached with chemical fertilizers compared with the respective manure treatment. In general, the results of 2005 indicate that the LHM application is beneficial in minimizing N leaching losses in coarse-textured soil compared with the chemical fertilizer application in a normal year. However, this difference was not evident in 2006, a year with below-normal growing season precipitation with smaller water percolation.

Soil residual N

There was a significant effect of amendment application on the residual soil NO_3-N concentration in 2005

Fig. 7. Residual soil nitrate and Mehlich 3 phosphorus (P) after harvest in the 0–120 cm depth in 2005 (*a* and *b*) and 2006 (*c* and *d*). The abbreviations M2500 and M5000 denote liquid hog manure application rates at 2500 and 5000 gal·ac^{-1}, respectively, whereas F2500 and F5000 denote chemical fertilizer application rates that provided total N and P in M2500 and M5000 treatments, respectively.



and 2006 ($p < 0.01$). Moreover, there was a significant effect of the rate of the amendment on the residual NO_3-N concentration in both years. In contrast, a significant effect of amendment type was obtained only in 2005 (Table 4).

The residual NO_3-N at soil surface was significantly greater in the F5000 treatment (24 ± 14 mg·kg^{-1} (mean ± standard deviation)) than the control (3 ± 1 mg·kg^{-1}) in 2005 ($p < 0.1$, Fig. 7). The F5000 treatment showed an elevated NO_3-N concentration throughout the soil profile, which corroborates the NO_3-N leaching load, where F5000 had the greatest amount of leached NO_3-N in 2005 (Figs. 7*a* and 6*a*). In 2005, the NO_3^--N concentration in the surface layer of F5000 was 1.5 times greater than that of M5000 (14 ± 6 mg·kg^{-1}) at harvest. However, in 2006, the near-surface residual soil NO_3-N of both F5000 and M5000 was smaller than the previous year (11 ± 5 and 10 ± 5 mg·kg^{-1}), and the previous year difference was not pronounced (Fig. 7*c*). In general, residual soil NO_3-N concentrations for 2006 were smaller than in 2005 due to lower N application rates.

The NO_3-N concentration at the 120 cm depth was significantly greater in F5000 when compared with control and M2500 treatments, and this was consistent for both 2005 and 2006 (Fig. 7). Wood et al. (1996) have shown that NO_3-N concentration in a silty clay soil that percolated below 1 m was greater under fertilizer (ammonium nitrate) than manure. The residual N at the 120 cm depth of F5000 treatment (26 ± 12 mg·kg^{-1}) in 2005 was approximately 1.5 times greater than M5000 (19 ± 14 mg·kg^{-1}), whereas residual N at the 120 cm depth of F2500 treatment (14 ± 12 mg·kg^{-1}) was six times greater than M2500 treatment (2 ± 0.6 mg·kg^{-1}). However, in 2006, the residual N at the 120 cm depth of F5000 and F2500 treatments (26 ± 16 and 3 ± 2 mg·kg^{-1}) were approximately three times that of their respective manure treatments (7 ± 6 and 1 ± 0.2 mg·kg^{-1} for M5000 and M2500, respectively). The amount of N remaining in the soil after the growing season is determined by a balance between plant uptake, N losses to the environment, and mineralization–immobilization processes (Ju and Zhang 2017). In general, the N availability from LHM in the year of application was approximately 60%–70% of that of urea-N (Qian and Schoenau 2000). The remaining N in LHM could become available for the subsequent crops or be lost to the environment. Therefore, attention should be paid to managing soil residual N within optimal levels.

Soil residual P

In general, residual P concentration was greater in the top 0–10 cm depth of the amended plots when compared with deeper layers, whereas it was close to that of the control below the 10 cm depth (Figs. 7*c*, 7*d*), showing limited mobility of P within the soil profile. As such, further discussion will be limited to the residual P concentration in the 0–10 cm soil layer. In 2005, the application of amendments significantly increased residual P concentration in the soil surface compared with the control treatment ($p < 0.01$). The residual P concentration in the control plot was 12 ± 5 and 10 ± 5 mg $P{\cdot}kg^{-1}$ in 2005 and 2006 (mean ± standard deviation), respectively. A significant effect of amendment type and application rate on the soil residual P concentration was observed in 2005, whereas the residual P concentration did not vary significantly between amendment type and application rates in 2006 (Table 4). The lack of a treatment effect in 2006 could be attributed to the smaller crop P uptake and leaching. The residual P concentration in amended plots was in the range of 19–23 mg $P{\cdot}kg^{-1}$ in 2005 except for M5000 that had a significantly greater soil test P concentration when compared with other treatments (37 ± 15 mg $P{\cdot}kg^{-1}$, $p < 0.1$). The residual P concentration in 2006 was higher as M5000 had 37 ± 18 mg $P{\cdot}kg^{-1}$, whereas M2500 had 25 ± 17 mg $P{\cdot}kg^{-1}$. In 2006, the soil residual P concentration for M5000 was also significantly greater than the control. It also should be noted that the M2500 and M5000 plots received LHM from 2002 to 2004 (Nikiema et al. 2013). Our results agree with those from previous studies that reported greater surface accumulation of P in soils amended with high rates of LHM (Royer et al. 2003).

Our results on soil residual P show that despite having the yield, N and P uptake, and N leaching reduction advantages, manure application should be handled carefully. Accumulation of P at the soil surface could further exacerbate runoff P losses (Wilson et al. 2019). Therefore, options like adopting four R principles (right source, right rate, right time, and right place) and production of low P manure or processing manures with low available P fractions (Kumaragamage and Akinremi 2018) should be considered.

We used two different crops (barley in 2005 and red spring wheat in 2006) in this study. The plant water and NUE could vary with crop types and cultivars. Therefore, our results should be used with caution. However, our findings on crop N uptake and N leaching are comparable with those of a companion study (Karimi and Akinremi 2018) on plant N utilization and N leaching in barley and red spring wheat crops. This study simultaneously assessed the N and P crop utilization and leaching potential when LHM and chemical fertilizers were applied to barley and wheat crops in coarse-textured soils. Our findings may differ from results in other soil texture due to the differences in denitrification rates and the existence of preferential flow pathways.

Conclusions

This study assessed crop performance, NO_3-N leaching, and soil N and P status when treated with LHM and chemical fertilizers in a sandy loam soil for two consecutive years. The LHM treatments produced significantly greater grain yields over control treatments. The LHM treatments also produced greater wheat grain yields in 2006 compared with chemical fertilizers with similar application rates. Grain N and P uptake under LHM treatments were also similar to or greater than that of chemical fertilizers. Based on leachates collected from lysimeters, chemical fertilizers posed a greater risk for NO_3-N leaching losses. However, the accumulation of P at soil surface was observed for M5000 treatment indicating potential P loss risk when LHM is applied in greater quantities. Findings from the current study also showed that the application of LHM at moderate levels (M2500) could be agronomically productive with potentially minimal environmental impacts.

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