Tillage system and time post-liquid dairy manure: Effects on runoff, sediment and nutrients losses

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Abstract

Liquid manure applied in agricultural lands improves soil quality. However, incorrect management of manure may cause environmental problems due to sediments and nutrients losses associated to runoff. The aims of this work were to: (i) evaluate the time effect of post-liquid dairy manure (LDM) application on runoff, sediment and nutrient losses; (ii) compare the effect of conventional tillage and no-till systems on runoff, sediment and nutrients losses after LDM application. A rainfall simulation experiment was conducted on intact soil blocks collected from fields that had been under conventional tillage and no-till systems. Rainfall was applied 24 hours or 7 days after LDM application. Conventional tillage without manure application resulted on higher runoff, sediment and nutrient losses (mainly the particulate fraction) than no-till without manure. The greatest runoff, sediment and nutrients losses occurred in the treatments where simulated rainfall was performed 24 hours after LDM application independent of the tillage system. An interval of 7 days between manure application and the simulated rainfall reduced mainly, sediment, particulate P, and particulate N losses in both, conventional and no-till systems. In practical terms, we would recommend a minimum of 7 days between LDM application and rainfall-runoff event to provide agronomic benefits minimizing the potential risk of water pollution.

Key words: Phosphorus, Nitrogen, No-till, rainfall simulation

1. Introduction

Liquid manures are commonly used in agricultural soils as effective sources of plant nutrients, as well as their potential to improve the chemical, physical, and biological properties (Adeli et al., 2008; Fares et al., 2008; Kheyrodin, 2011). However, inappropriate management of manure, such as application methods, excessive rates and timing of

application may cause negative effects on water quality (Allen and Mallarino, 2008; Kaiser et al., 2009; Lord, 1996).

Manure applied on soil surface is extremely vulnerable to nutrient losses as surface runoff into ditches and streams, especially when rainfall occurs shortly after application (Allen and Mallarino, 2008; Mori et al., 2009; Tabbara, 2003).

Phosphorus and nitrogen are essential for plant growth, but their application in agricultural fields should be carefully managed, because improper management may result in surface and subsurface water pollution (Casalí et al., 2008; Kato et al., 2009). Manure application without incorporating into the soil promotes stratification of P within the topsoil with high concentration of P at the soil surface and low potential for P sorption to the soil (Schwab et al., 2006; Sharpley, 2003). In no-till soils, the build-up of nutrients at the surface increases the potential for P and N loading to runoff water, especially in dissolved forms (Sharpley, 2003; Smith et al., 2007).

The transport of nutrients from soil to water may be as soluble or adsorbed to soil particles (mineral and/or organic). Generally, particulate P (P bounded to the sediment) dominates P loss on conventional agricultural systems (Kleinman et al., 2011; Verbree et al., 2010), so controlling the sediment loss as been considered as an effective way to reduce the nutrients loss. Management practices such as conservation tillage systems are effective in reducing soil erosion and consequently nutrient losses adsorbed to the sediment (particulate form), decreasing thus Total N and Total P (Bortolozo et al., 2015; Ramos et al., 2014; Sharpley et al., 2013; Sharpley and Wang, 2014).

The interval between manure application and the rainfall-runoff event have been shown to be an important factor affecting nutrient losses. Some studies show that when a rainfall event occur immediately after manure application, the P and N concentrations in runoff are greater than when the first rainfall occur in few days after application (Allen and

Mallarino, 2008; Smith et al., 2007; Tabbara, 2003). In this study, we are particularly interested in how the timing of the rainfall event affects sediment and nutrient runoff after surface application of liquid manure on undisturbed soil surfaces under different tillage practices.

A laboratory rainfall simulation experiment was designed to: (i) evaluate the time effect of post-liquid dairy manure application (LDM) on the water, sediment and nutrient losses; and (ii) compare the effect of conventional tillage and no-till systems on water, sediment and nutrients losses after LDM application. This study will provide recommendations of management practices on LDM that offer agronomic benefits with minimal potential risk of water pollution.

2. Material and Methods

2.1 Experimental site and treatments

This study was performed in the USDA-ARS-National Soil Erosion Research Laboratory at West Lafayette, Indiana. Undisturbed soil samples (Table 1) were collected from the 0-0.1 m layer in conventional tillage (CT) and no-till (NT) fields at the Throckmorton Purdue Agricultural Center (TPAC) in Lafayette, Indiana. The soil samples were collected using metal boxes with the dimension of 0.45 x 0.30 x 0.10 m. The study soil was a Raub loam soil (USDA-Soil Survey Staff, 1999).

Table 1

The experiment consisted of six treatments with three replicates: two tillage systems (CT and NT), two intervals between manure application and rainfall simulation, i.e., 24h and 7 days, and the control (CT and NT without DLM application). The liquid dairy manure (Table

2) at dosage of $60 \text{ m}^3 \text{ ha}^{-1}$ was manually applied on the soil surface and the rainfall simulation was performed 24 hours (24h) and seven days (7days) post-manure application.

The treatments were defined such: CT control and NT control (no manure added), CT 24h and NT 24h (rainfall simulation 24 hours after LDM application), CT 7days and NT 7days (rainfall simulation 7 days after LDM application).

Table 2

2.2 Simulated rainfall and runoff samplings

Simulated rainfall was applied using deionized water at an intensity of 50 mm h^{-1} for 60 minutes. The soil sample was set to 10% slope. Prior to each simulation, a pre-wetting low intensity rain of 12 mm h^{-1} was applied and the soil samples were equilibrated for 24 hours. This procedure minimized the differences between the antecedent soil water conditions among the treatments and resulted in all the soil samples near their field capacity before the 50 mm h^{-1} runoff-generating rainstorm.

During the 60 minute rainfall event, samples were collected every 5 minutes after runoff initiation. The runoff sample for sediment data was taken in a tared one-liter bottle for two minutes. Immediately after the sediment sample collection, additional runoff samples were taken for soluble and total nutrient analyses. Sediment runoff samples were weighed and then dried at 105°C . Runoff amounts and sediment concentrations were determined gravimetrically. For nutrient analyses, a sample of 60 mL was collected for total digestion (unfiltered samples), while a sample of 20 mL was filtered using $0.45 \mu\text{m}$ syringe filters to analysis soluble nutrients. Filtered and unfiltered samples were acidified with concentrated sulfuric acid to $\text{pH} < 2$ and were frozen to further chemical analysis.

To determine nutrient concentrations in the runoff samples, colorimetric analyses were conducted on a Thermo Scientific KoneLab 20 water chemistry auto-analyzer. Dissolved

reactive phosphorus (DRP), nitrate ($\text{NO}_3\text{-N}$) and ammonium ($\text{NH}_4\text{-N}$) were analyzed with EPA method 365.2, EPA method 353.1 and EPA method 350.1, respectively (U.S. EPA, 1979). Unfiltered water samples were digested with mercuric sulfate and then analyzed total Kjeldahl nitrogen (TKN) and total phosphorus (TP) with test method based on EPA method 351.2 rev 2 (O'Dell, 1993) and EPA method 365.4 (U.S. EPA, 1979). Particulate phosphorus (PP) was obtained by subtracting DRP from TP and particulate nitrogen (PN) was obtained by subtracting N-NH_4 from TKN. Total nitrogen (TN) was calculated by the sum between TKN and N-NO_3 .

2.3 Statistical analysis

Analysis of variance and Tukey's test ($P < 0.05$) for mean comparisons procedures and Pearson correlation analyses ($p < 0.05$) were performed using the StatSoft, Inc. (2011) STATISTICA data analysis software system, version 10.0. (www.statsoft.com).

3. Results and discussion

3.1 Runoff rate and sediment loss

Figure 1 shows the runoff and sediment discharge during the 60-minute simulated rainfall. The runoff rate during the simulated rainfall had similar behavior for CT control, CT 24h and NT 24h treatments. The runoff rate was lower in the beginning of the rain and after 5 min, it remained constant (Fig. 1A). This probably was due to surface sealing and clogging of pores from the LDM application (Barrington et al., 1987; Culley and Phillips, 1982) or by the raindrop splash (Bradford and Huang, 1994). For NT control, NT 7days and CT 7days, the runoff increased gradually (Fig. 1A). For NT control this behavior can be explained by the higher soil aggregation and stability that promoted greater infiltration. For treatment CT

7days, the dried manure possibly provided soil surface protection against raindrop impact (Barthès et al., 1999), and therefore, increased water infiltration.

Figure 1

The total runoff for the 60 min rain interval was higher for the CT 24h and NT 24h treatments ($\sim 42 \text{ mm h}^{-1}$) and lower for the NT 7days ($\sim 17 \text{ mm h}^{-1}$). Comparing the control and manured treatments, we observed that for conventional tillage the runoff increased 20% in CT 24h and reduced 14% in CT 7days, while for no-till the runoff rate increased 72% in NT 24h and reduced 32% in NT 7days (Table 3). Cherobim et al. (2015) in a study with no-till system, noted that the LDM application on the soil surface influenced the water infiltration mainly in the first five days, after that the infiltration rate was not different among treatments.

Table 3

The sediment loss during the rainfall event (Fig. 1B) followed the runoff loss pattern (Fig. 1A). Three treatments, i.e., CT control, CT 24h and NT 24h showed significantly greater sediment losses during the 1-hr rain, with the CT control treatment showing the greatest loss in the first few minutes. In conventional tillage, the higher losses occurred due the soil disaggregation (Meijer et al., 2013) that facilitated the particles transport through the runoff.

Regarding the cumulative sediment loss, CT control, NT 24h and CT 24h showed greater losses and these losses were not statistically different, while NT control and NT 7days showed less sediment losses (Table 3). Comparing CT treatments, a delay of 7 days after the manure application before the rain event caused a significant reduction in the sediment loss (~ 850 and $\sim 263 \text{ g m}^{-2} \text{ h}^{-1}$, respectively) around 70%. This result reinforces the idea of the

possible action of the manure on soil protection against disaggregation by rain drop, especially for conventional tillage.

When comparing tillage systems, our results clearly demonstrate that CT caused higher sediment loss than the NT system, reinforcing that tillage is the major factor driving the sediment loss in the runoff process (Beniston et al., 2015). The conservative tillage system, such as no-till, improves soil stabilization, water infiltration and water holding capacity (Cruse and Herndl, 2009; Sharpley and Wang, 2014), increases soil organic matter in the topsoil (Lal, 2003) and decreases the export of sediment in runoff water (Tiessen et al., 2010).

3.2 Nutrients loss

3.2.1 Phosphorus

The losses of different phosphorus fractions are presented in Figures 2A, C, E, and these losses are directly associated with their concentrations (Figures 2B, D, F). The results for TP and PP in the conventional tillage were similar. Treatment CT 24h showed high TP and PP losses in the first 30 minutes, then decreasing gradually. These losses are related to the concentrations of P bound to sediments. Losses of DRP the treatments CT 24h and NT 24h were also high in the beginning, and decreasing gradually (Fig. 2E). This phenomenon was caused by the high concentration of soluble P present in the LDM that results in greater P losses mainly in the first minutes of runoff. For other treatments, the losses of all forms of P were mostly constant during the rainfall event (Fig. 2A, B).

Figure 2

For cumulative P losses from the 1-h rain event, the total P was the highest in CT 24h (1527 mg m⁻²), followed by NT 24h (834 mg m⁻²). The high TP loss in the CT 24h is due to high PP loss. For CT 24h, the TP loss was 336% greater than that from the CT control, whereas TP loss from NT 24h was 916% greater as compared to NT control. Seven days after the manure application, TP from the CT 7days decreased by 80% as compared to the TP loss from CT 24h, while NT 7days decreased 88% as compared to NT 24h (Table 4). Comparing the control treatments in the partition of the P fractions, the percentage of TP as DRP was higher in the no-till than in the conventional tillage (i.e., 7.3% vs. 0.8%), while PP showed the inverse proportion (Table 5). However, in terms of cumulative losses, the conventional tillage lost 45 % less to DRP and 180 % more to PP, when compared to the no-till treatment (Table 4).

Table 4 and Table 5

The loss of particulate P was higher in 24h after manure application in both tillage systems. This occurred probably because the liquid manure recently applied in the surface had light organic matter that floated and was transported in the runoff (McDowell and Sharpley, 2002). After 7 days, the drying and crusting of manure decreased the availability of light organic matter to runoff and decreased the PP loss (Kleinman and Sharpley, 2003; Vadas et al., 2007). Due the lower aggregate stability, the CT treatment had greater loss of organic materials from LDM plus soil particles than those from the NT treatment.

The absence of a significant difference in total P loss between NT control and NT 7days and between CT control and CT 7days can be related to sediment loss, soil-bound P, and desorption of P. Johnson et al. (2011), working with dairy manure slurry in a no-till system and applying simulated rainfall 72 hours post application, did not find differences in

total P loss when compared control treatment and treatment with slurry applied in the soil surface.

In our study, the highest DRP loss occurred in the treatments with rainfall simulation 24 hours following LDM application, independent of the tillage system (Table 4). Johnson et al. (2011) also observed highest DRP loss in manured treatments when compared to control treatment (no manure). Dissolved reactive P decreased significantly in the treatments with 7 days post LDM application independent of tillage system. The P loss as DRP was highest for the first rainfall simulation after manure application and decreased after 7 days, however the loss remained greater than control treatments in both systems, demonstrating similar trends are those observed by Vadas et al. (2007). The time interval between manure application and runoff event has an essential role in the P losses. Avoiding manure application before a forecasted rainfall event is very important to minimize P losses (Schroeder et al., 2004; Allen and Mallarino, 2008). Moreover, it is worth emphasizing that the applied manures can contribute as dissolved P in runoff for a long time after they are applied on soil (Vadas et al., 2007).

3.2.2 Nitrogen

The losses of total N, particulate N, $\text{NO}_3\text{-N}$, and $\text{NH}_4\text{-N}$ are shown in Figures 3A, C, E and G, respectively, with the concentration data following similar trends as the mass loss (Figures 3B, D, F, H). Total N, particulate N and $\text{NH}_4\text{-N}$ had the same behavior, showing greatest losses occurred from the 24h treatment of both CT and NT systems, also during the first few minutes of the applied rainfall. The $\text{NO}_3\text{-N}$ loss from the NT 7days treatment show highest losses among all treatments during the one hour rainfall event, but the amounts were very small. The CT and NT control treatments behaved similarly, showing lowest losses

among all treatments independent of N-fractions. For total N, a rainfall event occurred 7 days after LDM application reduced the N loss independent of the tillage system.

Figure 3

For cumulative nitrogen losses (Table 4), the total N (TN) and particulate N (PN) losses were higher in the NT 24h and CT 24h treatments. The cumulative losses of TN and PN for NT control and NT 7days were significantly lower than others treatments. Increasing time between LDM application and rainfall event decreased the loss of $\text{NH}_4\text{-N}$, PN and TN, corroborating the results by Smith et al. (2007). Comparing cumulative loss of $\text{NH}_4\text{-N}$ in 24h versus 7days treatments, the loss was decreased 87% in CT and 96% in NT treatments. The cumulative loss for nitrate was higher in LDM treatments when compared to control treatments. The cumulative loss of $\text{NO}_3\text{-N}$ was higher in the NT 7days compared to other treatments, this probably occurred by the nitrification process (nitrifying bacteria). It is common for greater biological activities in no-till soils than in conventional tilled soils. Sharpley and Wang (2014) showed that conservative tillage caused an increase in nitrate and soluble P losses.

Among all the treatments, the biggest fraction of N concentration was as particulate N ($> 70\%$). In the control treatments, the particulate fraction was even higher, i.e., 99.5 and 95.8% in CT and NT, respectively (Table 5). It is common to have a strong correlation between the loss of particulate nutrients and sediment loss (Kleinman et al., 2011; Vadas et al., 2004). In our experiment, the PN concentration was positively correlated to sediment loss ($r = 0.73$).

High nutrient losses (Table 4) occurred 24h after manure application. This information is important in managing and planning manure applications in order to minimize the nitrogen

and phosphorus losses, mainly for those in the particulate fractions (sediment-associated). Therefore, manure management decisions should be made with attention to weather forecast to avoid field applications when there potential rainstorms are developing in the near future because the sooner the first rainstorm comes after the manure application, the risk of P and N losses to runoff water increases, and causing further environmental degradation.

4. Conclusion

Runoff, sediment and nutrient losses (mainly the particulate fraction) were affected by tillage systems. Without the manure application, conventional tillage resulted in higher losses than those from no-till system. The greatest fractions of nutrient losses were found in the particulate fraction, indicating erosion as the primary process associated with nutrient loss.

The time- post liquid dairy manure affected runoff, sediment and nutrients losses (except nitrate-N). In our research, the 24 hours post-manure application resulted in higher losses in conventional and no-till systems. Seven days after manure application, the losses were significantly decreased.

In practical terms, we would recommend, using weather forecast in making decisions on when to apply liquid dairy manure provide agronomic benefits and avoid risk of water pollution.

Acknowledgements

Authors are grateful to CAPES/Brazil for the scholarship and to the National Soil Erosion Research Lab-ARS-USDA/Purdue University for the field and laboratory support.

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Table 1. Soil characterization

Tillage system	Depth	Physical properties					Chemical properties						
		Sand	Silt	Clay	MWD	ρ_s	Ca ⁺²	Mg ⁺²	K ⁺	P Mehlich	NO ₃ -N	pH	OC
	m	g kg ⁻¹			mm	g cm ⁻³	mg kg ⁻¹					g kg ⁻¹	
CT	0-0.05	440	420	140	0.13	1.33	1522	302	296	140	19	6.4	14.5
CT	0.05-0.10	460	380	160	0.14	1.44	1572	317	218	80	22	6.5	12.8
NT	0-0.05	440	480	80	0.50	1.21	1974	300	422	122	5	6.8	23.8
NT	0.05-0.10	400	460	140	0.46	1.29	1670	321	265	94	6	5.9	13.9

CT: Conventional Tillage; NT: No-till; MWD: Mean Weight Diameter (wet); ρ_s : bulk density; NO₃-N: Nitrate Nitrogen; OC:

Organic Carbon

Table 2. Liquid dairy manure (LDM) characterization

	pH	Total dry solids	TKN	NH ₄ -N	TP	K	Ca	Mg	Na
		%	mg L ⁻¹						
LDM	7.5	3.5	2180	1430	360	1270	1300	603	596

TKN, Total Kjeldahl Nitrogen; NH₄-N, Ammonium Nitrogen; TP, Total Phosphorus; K, Potassium; Ca, Calcium; Mg, Magnesium; Na, Sodium.

Table 3. Cumulative losses of runoff and sediment for different tillage system and time post-manure application.

	CT Control	CT 24 h	CT 7 days	NT Control	NT 24 h	NT 7 days
Runoff (mm) ^a	35 ab	42 a	30 b	25 bc	43 a	17 c
Sediment (g m ⁻²) ^a	844.5 a	741.7 a	262.9 bc	105.3 c	595.7 ab	54.7 c

^a Means followed by the same letter are not significantly different by Tukey's test ($P < 0.05$).

CT: Conventional tillage; NT: No-till; Control: treatment without LDM application; 24-h: treatment with LDM and simulated rainfall 24 hours after LDM application; 7-days: treatment with LDM and simulated rainfall 7 days after LDM application.

Table 4. Cumulative loss and average concentration of dissolved reactive P (DRP), particulate P (PP), total P (TP), soluble $\text{NH}_4\text{-N}$, soluble $\text{NO}_3\text{-N}$, particulate N (PN), and total N (TN) in runoff for different tillage system and time post-manure application.

	DRP	PP	TP	$\text{NH}_4\text{-N}$	$\text{NO}_3\text{-N}$	PN	TN
Loss (mg m^{-2}) ^a							
CT Control	2.71 d	453.4 b	456.1 c	1.54 d	4.91 b	1279 b	1285 b
CT 24 h	410.9 a	1116 a	1527 a	558.1 a	16.4 ab	3374 a	3948 a
CT 7 days	100.2 b	209.7 b	309.9 c	71.3 b	22.9 ab	1214 b	1308 b
NT Control	6.09 d	85.3 c	91.4 d	1.73 d	6.27 b	230.2 c	238.2 c
NT 24 h	530.2 a	303.4 b	833.7 b	482.7 a	17.1 ab	3194 a	3694 a
NT 7 days	48.8 c	51.2 c	99.3 d	18.5 c	50.8 a	210.2 c	279.5 c
Concentration (mg L^{-1}) ^a							
CT Control	0.08 d	12.7 b	12.8 c	0.04 d	0.15 c	36.2 c	36.4 bc
CT 24 h	10.7 a	29.1 a	39.8 a	13.6 a	0.42 bc	86.6 a	100.6 a
CT 7 days	3.22 b	6.21 c	9.43 c	2.35 b	0.83 b	36.5 c	39.7 b
NT Control	0.25 c	3.19 d	3.44 d	0.07 d	0.31 bc	8.62 d	9.18 d
NT 24 h	12.9 a	6.87 c	19.8 b	11.6 a	0.42 bc	79.9 ab	92.0 a
NT 7 days	2.79 b	2.74 d	5.53 d	1.12 c	3.71 a	11.6 d	16.4 cd

^a Means followed by the same letter in the column are not significantly different by Tukey's test ($P < 0.05$).

CT: Conventional tillage; NT: No-till; Control: treatment without LDM application; 24-h: treatment with LDM and simulated rainfall 24 hours after LDM application; 7-days: treatment with LDM and simulated rainfall 7 days after LDM application.

Table 5. Percentage of the total P (TP) as dissolved reactive P (DRP) and particulate P (PP) and of the total N (TN) as ammonium (NH₄-N), nitrate (NO₃-N) and particulate N (PN) for the treatments calculated using the average concentration in runoff for different tillage systems and time post-manure application.

	CT Control	CT 24 h	CT 7 days	NT Control	NT 24 h	NT 7 days
	% of TP as DRP and PP					
DRP	0.8	26.9	34.1	7.3	65.0	50.5
PP	99.2	73.1	65.9	92.7	35.0	49.5
	% of TN as NH ₄ -N, NO ₃ -N and PN					
NH ₄ -N	0.1	13.5	5.9	0.8	12.6	6.8
NO ₃ -N	0.4	0.4	2.1	3.4	0.5	22.5
PN	99.5	86.1	91.9	95.8	86.9	70.6

CT: Conventional tillage; NT: No-till; Control: treatment without LDM application; 24-h: treatment with LDM and simulated rainfall 24 hours after LDM application; 7-days: treatment with LDM and simulated rainfall 7 days after LDM application.

Fig 1. Runoff rate (A) and sediment loss (B) under a single rainfall ($\sim 50 \text{ mm h}^{-1}$) for 1 hour in conventional tillage (CT) and no-till (NT) and time post-manure application (24h and 7days).

Fig 2. Total P (A, B), Particulate P (C, D), and DRP (E, F) under a single rainfall ($\sim 50 \text{ mm h}^{-1}$) for 1 hour in conventional tillage (CT) and no-till (NT) and time post-manure application (24 h and 7 days).

Fig 3. Total N (A, B), Particulate N (C, D), NO₃-N (E, F), and NH₄-N (G, H), under a single rainfall (~50 mm h⁻¹) for 1 hour in conventional tillage (CT) and no-till (NT) and time post-manure application (24 h and 7 days).