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Surface Water Quality

Tillage and manure effects on runoff nitrogen and phosphorus losses from frozen soils

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Abstract

In cold regions, nutrient losses from dairy agroecosystems are a longstanding and recurring problem, especially when manure is applied during winter over snow-covered frozen soils. This study evaluated two tillage (fall chisel tillage [CT] and no-tillage [NT]) and three manure-type management treatments (unmanured control, liquid manure [<5% solids], and solid manure [>20% solids]). The liquid and solid manure used in this study were from the same animal species (*Bos taurus*) and facility. The six management treatments were field tested in south-central Wisconsin during the winters (November–April) of 2017–2018 and 2018–2019 with a complete factorial design. Seasonal runoff losses were significantly lower from fall CT compared with NT during both seasons. Manure applications (both liquid and solid) on top of snow significantly increased most of the nutrients (NH_4^+, dissolved reactive phosphorus, total Kjeldahl nitrogen, and total phosphorus) in runoff compared with unmanured control. Irrespective of tillage and multiple runoff events, solid manure was present on the surface for longer periods, potentially releasing nutrients each time it interacted with runoff. In contrast, liquid manure infiltrated the snowpack and was partly lost with snowmelt and infiltrated soil depending upon soil frost and surface conditions. Overall, results indicate that wintertime manure applications over snow-covered frozen soils pose a risk of nutrient loss irrespective of tillage and manure type, but in unavoidable situations, prioritizing tillage × manure type combination can help reduce losses.

1 | INTRODUCTION

In cold agricultural regions, soils undergo freezing and thawing during winter months and are temporarily covered with snow. In some of these regions (the midwestern and northeastern United States, British Columbia, Alberta, and Saskatchewan), land application of manure during winter is practiced for various economical and management reasons (Liu et al., 2018). In spite of local directives and guidance on application, this practice is associated with elevated runoff risks and manure nutrient losses because of frozen soil conditions, snowmelt, and rain-on-snow events (Liu et al., 2018; Srinivasan et al., 2006). Such nutrient losses can lead to fish kills, eutrophication, degraded freshwater quality, and other environmental issues (Carpenter et al., 1998).

Abbreviations: CT, chisel tillage; DRP, dissolved reactive phosphorus; NT, no-tillage; TKN, total Kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus; TS, total solids; VS, volatile solids.

Challenges with long-term manure storage and costs associated with storage infrastructure are some of the practical reasons for winter manure application (Srinivasan et al., 2006). However, an 11-yr watershed-scale modeling study conducted in Pennsylvania found that 12 mo of storage and applying all manure in one application (spring) did not reduce annual phosphorus (P) loads compared with 6 mo of storage and two (fall and spring) manure applications or 3 mo of storage and four (fall, winter, spring, and summer) applications (Liu et al., 2017), suggesting that long-term storage does not necessarily benefit the environment. Logistically, applying manure in winter avoids issues with farm labor availability and reduces the risk for soil compaction (Srinivasan et al., 2006). Moreover, a recent survey conducted in Michigan found that a total ban on winter manure application would cost small livestock farms US$30 million per year (Miller et al., 2017). Recent research advances and processing technologies are providing solutions to manure management through anaerobic digestion, solid-liquid separation, and granulating the manure (Aguirre-Villegas et al., 2014; Holly et al., 2017; Sharara et al., 2017, 2018). However, these technological solutions are not immediately available to all farmers, and winter manure application may not be avoided but rather needs to be facilitated by carefully considering the farmer's needs and simultaneously conserving environmental quality.

Nutrient loss from winter manure application has been a research topic since Midgley and Dunklee (1945) first identified that spreading manure on snow-covered fields leads to contamination of water bodies. Since then, studies have been conducted at different experimental (laboratory, field, watershed) scales and in different regions to identify appropriate practices for winter manure application. Laboratory-scale studies mainly investigated nutrient release characteristics of manure types (liquid, semi-solid, and solid) by varying their placement (below the snow, in between snow layers, and on top of snow), snowpack depths, surface slopes, and air and snowmelt temperatures (Steenhuis et al., 1981; Vadas et al., 2018; Williams et al., 2011).

Field-scale studies that evaluated similar laboratory conditions as the studies mentioned above had contrasting results. For example, slope had a minimal effect on nitrogen (N) losses under laboratory conditions (Steenhuis et al., 1981), whereas field-scale studies found slope had a major role on snowmelt and rainfall-induced runoff (Lewis & Makarewicz, 2009). Similarly, varying manure placement within the snowpack had no effect on nutrient release in a laboratory study (Vadas et al., 2018), but some field studies found that applying manure before snowpack accumulation resulted in less dissolved reactive P (DRP) loss than applying it on top of the snowpack (Stock, Arriaga, Vadas, Good, et al., 2019; Williams et al., 2011). Incorporating manure into the middle of the snowpack provided similar benefits to incorporating it into the soil (Williams et al., 2011). Discrepancies between laboratory and field studies are caused by varying environmental conditions and suggest that replicating experiments at different spatial and temporal scales is necessary to provide strong evidence-based guidance on winter manure application.

Core Ideas

- Fall chisel tillage reduced wintertime runoff and nutrient losses compared with no-tillage.
- Manure application on snow-covered frozen soil significantly increased runoff nutrient loads.
- Solid manure remained on the soil surface longer than liquid manure.
- Winter manure application should consider manure characteristics and field storage capacities.

Field-scale and watershed-scale studies have investigated interaction effects of winter manure application and tillage management while understanding underlying hydrological and nutrient transport processes (Good et al., 2019; Hoffman et al., 2019; Plach et al., 2019; Stock, Arriaga, Vadas, Good, et al., 2019; Vadas et al., 2019). Studies focused on fall tillage with winter manure application found that mechanically disturbed soil surfaces had increased surface roughness, which provided more time for snowmelt infiltration and reduced subsequent runoff and manure nutrient losses compared to no-tillage (NT) with winter manure application (Starkloff et al., 2017; Stock, Arriaga, Vadas, Good, et al., 2019; Young & Mutchler, 1976). Fall nutrient applications (injection or surface broadcast) before the soil freezes reduced surface nutrient losses in some studies (Stock, Arriaga, Vadas, Good, et al., 2019; Vadas et al., 2019), whereas spring applications reduced nutrient losses in others (Liu et al., 2017; Young & Holt, 1977; Young & Mutchler, 1976).

Kongoli and Bland (2002) found that solid manure (>20% solids) applied on snowpack significantly retarded the snowmelt rate and provided more time for snowmelt and manure nutrients to infiltrate into the soil. However, in this study, snow was completely covered with an even thick solid manure layer (3.5 cm), which is an atypical application method. Solid manure application with farm equipment typically leaves areas with and without manure at short spatial scales (<0.5 m^2). Also, the Kongoli and Bland (2002) study was not statistically replicated nor compared to liquid manure. Komiskey et al. (2011) compared nutrient losses from dairy liquid and solid beef manure on NT fields and found no differences. Young and Mutchler (1976) and Young and Holt (1977) investigated the effects of solid manure application timing and found that spreading manure on top of snowpack rather than before snowfall resulted in less runoff and nutrient loss.

The above-discussed studies investigated a wide range of scenarios and added substantial knowledge for guiding wintertime land application of manure. However, the contradicting results among different studies can at least be partially attributed to differences in study design, dynamic site-specific weather and soil conditions, and a lack of normalization/statistical methods to analyze the hydrologic, timing of application, and manure property controls on wintertime nutrient losses. Also, comparisons of wintertime nutrient losses from different manure types of the same animal species and their interactions with tillage management are lacking. Understanding how solid and liquid manure of the same animal species interact with snow and soil and how nutrients are lost in runoff during winter conditions will help guide winter manure applications. Overall, this study aims to increase knowledge of wintertime surface nutrient losses from frozen and snow-covered soils that receive late winter manure. The specific objective of this field study is to quantify tillage (CT and NT) and winter manure type (liquid, solid, and unmanured control) effects on wintertime (November–April) surface runoff, N, and P losses. Here, we hypothesize that fall CT will reduce runoff through increased surface roughness and that solid manure applications will result in greater nutrient losses than liquid manure.

2 | MATERIALS AND METHODS

2.1 | Experimental site and treatments

A field study was conducted in south-central Wisconsin at the University of Wisconsin-Madison Arlington Agricultural Research Station (43˚17′ N, 89˚21′ W). The field site was under alfalfa (*Medicago sativa* L.; 2011–2014) before transitioning into the experimental research site. Since the conversion (2015 onward), the site has been under corn (*Zea mays* L.) silage production (7), with all field operations performed along the contour. The site consists of 18 plots (5 m by 15 m each) with a 5.8% slope and a south-facing aspect on silt-loam soil (fine, mixed, superactive, mesic Oxyaquic Argiudolls) (Soil Survey Staff, 2022). Prior to this study (2015–2017), the plots were used to investigate the effects of tillage (CT vs. NT) and dairy liquid manure application timing (early-December vs. late-January application) on surface runoff and associated nutrient losses (Stock, Arriaga, Vadas, Good, et al., 2019). Manure and tillage treatments from prior work did not result in significant differences in P content of the soil (0–15 cm; data not shown).

In this study, two tillage and three manure type treatments were triplicated and evaluated in a complete factorial design. Fall CT and NT were evaluated as the main plot treatments, and the three manure-type treatments (liquid manure, solid manure, and unmanured control) were evaluated as subplot treatments. Fall CT is commonly practiced in corn production systems and, in contrast to NT, produces a rough soil surface (ridges and depressions). Tillage and manure type treatments were assigned randomly to the experimental plots. Data were collected during the 2017–2018 and 2018–20919 winter seasons (November–April). Each year after harvest, CT plots were tilled using a chisel plow, and NT plots were not disturbed. All plots were planted in spring (early May) for corn silage (Dekalb DKC 45-07 RIB hybrid) production and received 20 and 52 kg ha^{-1} of N and P_2O_5 at planting. Additionally, at V5-6 crop stage, 77 kg ha^{-1} of N was applied. After harvest, in all plots, little residue remained on the soil surface, with only 20-to-30-cm stalks standing upright. Manual manure applications were performed in January by distributing the manure (both liquid and solid) uniformly across plots using buckets (0.01 m^3). The date of application in both seasons was chosen based on when the following conditions were met: (a) snowpack depth on the plots was between 12 and 15 cm and (b) no snowmelt or rain-on-snow runoff event was forecast within 5 d after manure application. Liquid (<5% solids) and solid (>20% solids) manure types used in this study had different nutrient contents. Manure samples were analyzed by the University of Wisconsin Soil and Forage Analysis Laboratory (Marshfield, WI). Total N (TN) was measured by wet Kjeldahl method (Peters et al., 2003), and total P (TP) was measured after dry ashing with colorimetric spectrophotometry (Peters et al., 2003). Details of manure characteristics and application dates are presented in Table 1. The liquid manure application rate (37.6 Mg ha^{-1}) was a function of local regulations (Table 1). In the first year of experiments (2017–2018), we attempted to match the nutrients applied through liquid and solid manure (based on analysis of manure samples). However, post-application analysis revealed less nutrients were applied through solid manure than liquid manure (Table 1). To maintain consistency across years, application rates in 2018–2019 were kept similar to 2017–2018. Liquid and solid manure were collected from a dairy cow (*Bos taurus*) milking operation. Liquid manure was collected after agitation from a storage basin by pumping into a large storage tank for transport, and solid manure was scraped from the animal barn on the day of application.

2.2 | Field measurements and analysis

The field site was equipped with an onsite weather station to measure air temperature (model VP-3, Meter Group Inc.) and precipitation (snow water equivalent and rainfall) (HOBO RG3, Onset Computer Corporation with CS705, Campbell

TABLE 1 Details of manure application dates, application rate, density, dry matter (DM), total N (TN), and total P (TP) content

Season	Application date	Type	Application rate	Density	DM	Nutrient content		Nutrient applied	
						TN	TP[a]	TN	TP
			Mg ha^{-1}	kg m^{-3}	%	—% of DM—		—kg ha^{-1}—	
2017–2018	18 Jan. 2018	liquid	37.6	1,006.5	5.8	2.1	0.9	102.1	41.3
		solid	20.6	1,080.0	25.3	0.7	0.3	70.5	28.5
2018–2019	24 Jan. 2019	liquid	37.6	998.1	5.8	2.1	0.8	100.5	36.2
		solid	20.6	1,247.0	35.8	0.4	0.2	55.5	34.7

[a]The TP content presented is equivalent to P_2O_5.

Scientific). After fall harvest and before performing tillage operations, intact soil cores (10 cm) were collected from each experimental plot and oven-dried to measure dry bulk density. Liquid and solid manure densities were measured on-field using buckets (0.01 m^3) prior to their land application. Snow depth inside each plot was taken as the average measured by three snow sticks installed equidistant along the length of each plot. Soil frost depths were monitored weekly at a fixed location in each plot using frost tubes to determine frost formation and depletion (Rickard & Brown, 1972). Each plot was also equipped with a runoff collection system (Bonilla et al., 2006) to facilitate capture up to 152 mm of runoff per event. At the end of each runoff event, depths were measured in the collection system, and runoff subsamples were collected for laboratory analysis. Half of each subsample was filtered (0.45 μm) and analyzed for DRP (Murphy & Riley, 1962) and ammonium (NH_4^+) on a Lachat automated analyzer (Hach Company) using Quick Chem Methods 12-107-06-2-A. The unfiltered samples were analyzed for total solids (TS), volatile solids (VS) (APHA, 1995), and total Kjeldahl N (TKN) and TP were analyzed calorimetrically using an AQ2 Discrete Analyzer (SEAL Analytical).

2.3 | Statistical analysis

Seasonal runoff (November–April) was calculated by summing event runoff depths. Event nutrient loads were calculated using nutrient concentrations and runoff volumes, and they were summed to obtain seasonal losses (November–April). Statistical analyses were performed on the seasonal losses for each experimental year separately. Data were modeled using linear and mixed-effects models in R software (R Core Team, 2020). For facilitating the statistical analysis, two adjacent treatment pairs were treated as a block. Each block consisted of a pair of CT and NT plots, which were randomly assigned with manure-type treatments. Tillage, manure type, and their interactions were treated as fixed effects. Block and block × tillage were treated as random effects. Logarithmic data transformations were performed on all variables for normalization. Residual plots of modeled data were developed to identify randomly distributed errors and homogeneous variances. Fixed effects of tillage, manure type, and tillage × manure type were assessed separately by the differences of estimated marginal means using Kenward–Roger degrees of freedom at the 90% significance level. Additionally, pairwise comparisons were made between tillage, manure type, and tillage × manure type treatment pairs ($\alpha = .1$).

Weekly measured frost depths and frost formation or depletion rates were statistically analyzed similarly to seasonal runoff and nutrient losses. Frost formation or depletion rates (cm d^{-1}) were calculated by dividing the average change in frost depth with the number of days. For example, the frost formation rate between 7 and 14 November is calculated by subtracting the frost depth measured on 7 November from the frost depth measured on 14 November and then dividing by 7 d.

Seasonal nutrient losses from tillage × manure type treatments were normalized to account for differences in the applied nutrient content of the two manure types and potential losses contributed by the soil as follows. Nutrient losses from the tillage-control treatment were subtracted from the corresponding tillage–manure type treatment and divided by the amount of nutrient applied through manure (Equation 1). For example, DRP losses of CT–control treatment were subtracted from the DRP losses of CT–liquid manure treatment and divided by the amount of P applied through liquid manure. Fixed effects of tillage × manure type were assessed on the normalized nutrient losses, and pairwise comparisons were made at the 90% significance level. All significance tests were conducted on logarithmically transformed data, and the back-transformed means are presented in the tables and figures.

$$\text{Nutrient loss}_{\text{normalized}} = \frac{\text{Nutrient loss}_{\text{treatment}}\ (\text{g ha}^{-1}) - \text{Nutrient loss}_{\text{control}}\ (\text{g ha}^{-1})}{\text{Nutrient applied}\ (\text{kg ha}^{-1})} \quad (1)$$

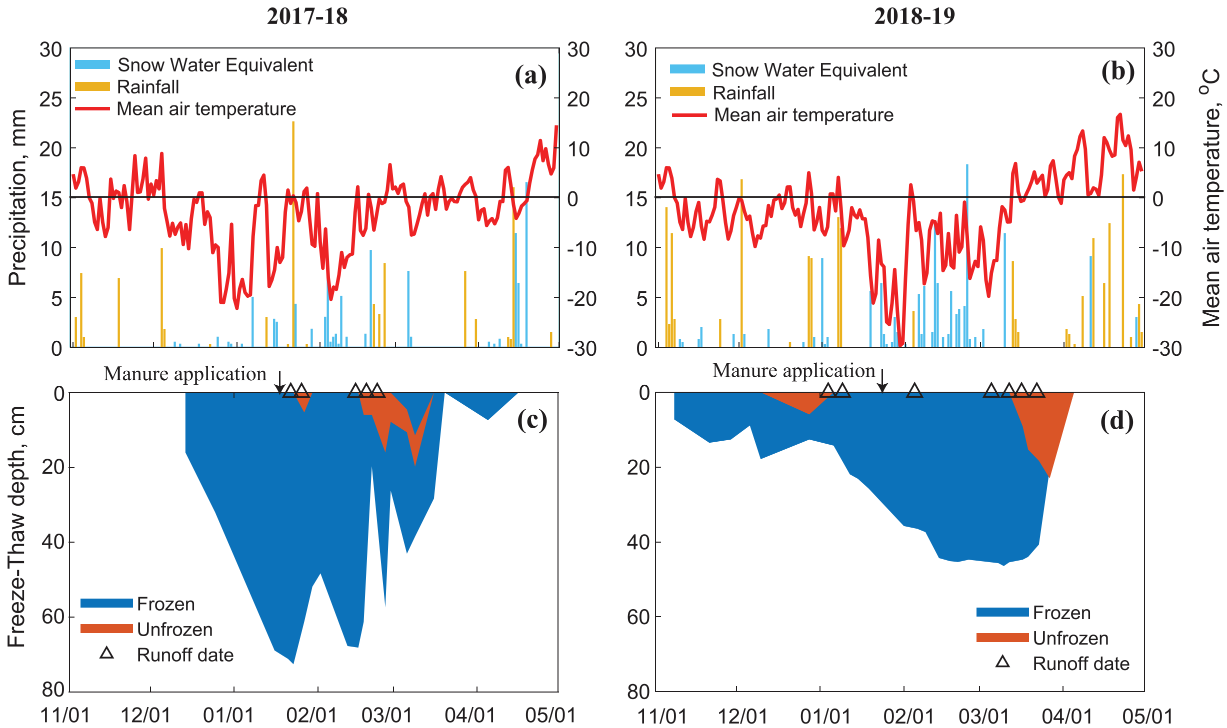

FIGURE 1 (a and b) Average daily air temperature and total daily precipitation as rainfall or the liquid-equivalent of snowfall (c and d) and soil frost formation and depletion during the 2017–2018 and 2018–2019 experimental seasons. Triangle indicates the runoff event date, and the arrow indicates date of manure application

3 | RESULTS AND DISCUSSION

3.1 | Weather

The normal (1991–2020 average) precipitation amounts from November to April (winter period) and May to October (non-winter period) are 305 and 596 mm, respectively, for Arlington, WI (National Weather Service, 2022). The wintertime during the study years (2017–2018 and 2018–2019) was drier than normal, with 43 and 11% less precipitation, respectively. The non-wintertime precipitation was 14% less (2017–2018) and 46% greater (2018–2019) than normal. The wintertime air temperatures were 0.8–6.1 ˚C colder than normal (−1.4 ˚C) during the experimental years. Air temperatures dropped below 0 ˚C earlier in 2018–2019 than in 2017–2018 (Figure 1a,b). However, December and April of 2017–2018 were 3.8 and 5.2 ˚C colder than in 2018–2019, respectively.

3.2 | Soil freeze–thaw dynamics

In seasonally frozen soils, soil frost strongly affects surface runoff characteristics by blocking soil pores with ice and reducing infiltration rates (Appels et al., 2018; Kane, 1980). In both years, soil frost formation and depletion responded similarly to air temperatures despite differences in snowpack amount and timing. No significant differences (data not shown) were observed in either frost formation or depletion rates (cm d^{-1}) or average depth of frost between tillage and manure type treatments. Therefore, average depths from all experimental treatments are presented (Figure 1c,d) as representative of that season, and only seasonal differences are discussed here. In 2017–2018, the earliest soil frost was observed on 9 Dec. 2017. In 2018—2019, soil started freezing earlier than in 2017–2018, with frost measured on 8 Nov. 2018. Despite the later onset, the soil froze faster and deeper in 2017–2018 than in 2018–2019. The maximum frost depth observed was 73 cm in 2017–2018 and 48 cm in 2018–2019. Maximum frost depths were observed after 45 and 112 d after the onset of frost in 2017–2018 and 2018–2019, respectively. Frost depletion was faster than formation, and all the frost disappeared within 10 d after the average air temperatures were >2 ˚C continuously for more than 2 d. In 2017–2018, frozen and unfrozen layers were observed within the soil profile. During the period of 18–28 Feb. 2018, soil thawed to a depth of 16 cm from the surface and remained frozen below 16 cm. Starting 6 Mar. 2018, soil started re-freezing from the surface, and from 6–10 Mar. 2018 the soil had a frozen layer at the surface (0–11 cm), an unfrozen layer at 11–20 cm, and another frozen layer at 20–38 cm. These dynamic soil conditions (frozen-unfrozen-frozen) are rarely reported in studies of seasonally frozen soils. Most studies report freezing and thawing as a one-dimensional process (soil freezes from the surface and thaws from both the surface and subsurface) and

TABLE 2 Seasonal runoff, nutrient loads, and ANOVA summary for tillage, manure type and tillage × manure interaction effects for the 2017–2018 monitoring season

Treatment effect	Treatment	Runoff	Nutrient load					
			TS	VS	NH_4^+	DRP	TKN	TP
		mm	kg ha^{-1}					
Tillage	CT	17.2b	147 ns	36.4 ns	0.28b	0.13b	0.97b	0.23b
	NT	30.2a	200	79.7	0.99a	0.49a	3.48a	0.79a
Manure type	control	23.3 ns	151 ns	30.5 ns	0.11b	0.05b	0.83b	0.18b
	liquid	20.9	207	102	1.01a	0.45a	2.04a	0.49a
	solid	24.2	160	50.4	1.32a	0.43a	3.65a	0.87a
Tillage × manure type	CT–control	18.7 ns	213 ns	40.6 ns	0.10c	0.02b	0.79b	0.12 ns
	NT–control	29.1	107	22.9	0.12c	0.11b	0.87b	0.28
	CT–liquid	13.3	133	54.1	0.39b	0.18b	0.74b	0.19
	NT–liquid	32.7	321	191	2.58a	0.73a	5.61ab	1.24
	CT–solid	20.3	111	21.9	0.56b	0.22b	1.53ab	0.53
	NT–solid	28.8	231	116	3.10a	0.63a	8.71a	1.45
ANOVA *p* value	tillage	.03	.64	.35	<.01	<.01	.01	.03
	manure type	.68	.73	.42	<.01	<.01	.01	.02
	tillage × manure type	.30	.30	.52	.02	.03	.07	.45

Note. CT, chisel tillage; DRP, dissolved reactive P; NT, no-tillage; TP, total P; TKN, total Kjeldahl N; TS, total solids; VS, volatile solids. Different letters in the same column and within the same treatment effect indicate a significant difference at $p < .1$ (ns, not statistically significant within the same factor at the .1 probability level).

do not report a series of frozen and unfrozen layers irrespective of geographic location (Iwata et al., 2010; Lindstrom et al., 2002; Stock, Arriaga, Vadas, Good, et al., 2019). Such layering can affect the hydrology (runoff and infiltration) of frozen soils and emphasizes the importance of monitoring soil frost to improve understanding of frozen soil hydraulic characteristics for modeling and predicting wintertime runoff in cold regions.

3.3 | Surface runoff

Five runoff events were recorded in 2017–2018, and seven events were recorded in 2018–2019 (Figure 1c,d). Surface runoff was observed from all treatment plots during each event, but event-based runoff depths differed among treatments. Total seasonal runoff depth (Nov–Apr) was higher in 2018–2019 than in 2017–2018, irrespective of tillage and manure-type treatment (Tables 2 and 3). This was expected because precipitation in 2018–2019 was 54% greater compared with 2017–2018. In both years, differences in runoff depths among the tillage treatments were significant ($p = .03$). The NT system produced two and three times greater runoff depths than CT in 2017–2018 and 2018–2019, respectively. Moreover, NT produced 21–100% greater runoff depths in 9 out of 12 events across the two experimental seasons than CT, indicating that NT was more prone to wintertime runoff losses. Similar results in previous studies are mainly attributed to ridges and furrows in mechanically disturbed (CT, moldboard tillage, etc.) soil holding rainfall and snowmelt water and providing more time for infiltration, whereas the relatively smoother surface in NT accelerates surface runoff before it can infiltrate (Stock, Arriaga, Vadas, Good, et al., 2019; Young & Mutchler, 1976).

All runoff events during both years of study occurred on frozen soil or soil with discontinuous frozen layers. Soil infiltration rates were not measured; however, depending upon the soil moisture content prior to freezing, frozen soil is likely to have minimal infiltration capacity, making surface storage important for controlling runoff (Shanley & Chalmers, 1999). A tile drainage study conducted in Canada measured subsurface hydraulic conductivity at various depths using piezometers and found frozen soil had lower conductivity compared with thawed (wet and dry) soil (Kokulan et al., 2021). In our experimental plots, soil moisture at 8 cm depth was consistently 15–52% higher prior to soil freezing in NT than CT (data not shown include information from the current study [2017–2019] and a prior study [2015–2017] [Stock, Arriaga, Vadas, Good, et al., 2019] on the same experimental plots). The higher soil moisture content likely leads to higher pore-ice formation and blockage of pores because soil water expands by 9–10% when frozen (Anderson & Tice, 1973), reducing infiltration compared with drier soils at the onset of frost.

Differences in runoff can also be attributed to differences in soil bulk density. The average bulk density (0–10 cm) measured from 2017 to 2019 prior to fall tillage was higher in NT (1.2 g cm^{-3}) than CT (1.0 g cm^{-3}). The higher bulk density

TABLE 3 Seasonal runoff, nutrient loads, and ANOVA summary for tillage, manure type, and tillage × manure interaction effects for the 2018–2019 monitoring season

Treatment effect	Treatment	Runoff	Nutrient loads					
			TS	VS	NH_4^+	DRP	TKN	TP
		mm	kg ha^{-1}					
Tillage	CT	24.9b	25.2b	17.1b	0.14 ns	0.07b	0.64b	0.14b
	NT	78.0a	87.8a	67.4a	0.60	0.36a	2.17a	0.51a
Manure type	control	47.0 ns	42.8 ns	31.1 ns	0.08b	0.04b	0.52b	0.10b
	liquid	51.7	55.1	43.2	0.76a	0.46a	1.49a	0.49a
	solid	35.2	44.1	29.2	0.45a	0.24a	2.12a	0.37a
Tillage × manure type	CT–control	29.8 ns	30.1 ns	17.0 ns	0.03 ns	0.01 ns	0.29 ns	0.06 ns
	NT–control	74.0	60.8	56.9	0.17	0.08	0.95	0.17
	CT–liquid	28.2	25.2	23.6	0.27	0.25	0.75	0.23
	NT–liquid	94.7	121	79.1	2.10	0.86	2.99	1.06
	CT–solid	18.3	21.1	12.5	0.32	0.08	1.24	0.20
	NT–solid	67.6	92.3	68.2	0.63	0.67	3.61	0.71
ANOVA *p* value	tillage	.03	.06	.07	.19	.05	.06	.03
	manure type	.32	.69	.70	.06	<.01	.07	.01
	tillage × manure type	.79	.49	.86	.54	.38	.93	.78

Note. CT, chisel tillage; DRP, dissolved reactive P; NT, no-tillage; TKN, total Kjeldahl N; TP, total P; TS, total solids; VS, volatile solids. Different letters in the same column and within the same treatment effect indicate a significant difference at $p < .1$ (ns, not statistically significant within the same factor at the .1 probability level).

may have negatively affected hydraulic conductivity (Nawaz et al., 2013), further contributing to the higher runoff from NT systems.

Application of manure on top of the snowpack can affect snowmelt rates and subsequent runoff volumes depending on the physical characteristics of the manure (Kongoli & Bland, 2002; Stock, Arriaga, Vadas, Good, et al., 2019). During 2017–2018, manure application occurred on 127 mm of snow-covered soil frozen to a depth of 69 cm (Figure 1c), and in 2018–2019, manure application occurred on 152 mm of snow-covered soil frozen to a depth of 27 cm (Figure 1d). Differences in seasonal runoff depth across different manure-type treatments were not statistically significant during both monitoring seasons (Tables 2 and 3). The frequency of runoff collection did not allow the estimation of snowmelt rates. However, manure and snow interactions provided some insights. Liquid manure, when applied, infiltrated and remained in the snowpack, leaving the coarser particles at the snow surface (Stock, Arriaga, Vadas, & Karthikeyan, 2019). Solid manure, because of its higher solids content, did not infiltrate into the snowpack at the time of application but rather remained on the snow surface, and after snowpack melted it remained on the soil surface. According to Stock, Arriaga, Vadas, & Karthikeyan (2019), snowpack that received liquid manure absorbed more radiative energy, which accelerated snowmelt and increased runoff volumes than snowpack without liquid manure. Similarly, dust deposition on alpine snowpack absorbed more radiation, which enhanced the snow melting rate compared with snowpack without dust (Skiles et al., 2012). During 2017–2018, snowpack on the liquid manure plots melted 2.1 cm d^{-1} faster than other treatments, supporting the finding of Stock, Arriaga, Vadas, & Karthikeyan (2019) and Skiles et al. (2012) that the dark color of liquid manure increases the radiative absorption and accelerates melting. In 2018–2019, after manure application on 24 Jan. 2019, consecutive snowfall events covered the treatment plots with 200 mm of snow before any melting event occurred, resulting in similar melting patterns across all treatments irrespective of manure type.

There were no significant differences in runoff depths with the combined effects of tillage and manure type in either year of the study (Tables 2 and 3). Overall, tillage management can strongly affect wintertime surface hydrology of cold-region dairy agroecosystems, especially fields with corn silage, which typically leaves <30% surface residue (Liu et al., 2019; Stock, Arriaga, Vadas, Good, et al., 2019). As previously mentioned, NT can accelerate and produce greater runoff during frozen ground periods because soil pores can get plugged with ice, and the surface lacks depressional storage. Chisel tillage along the contour creates surface roughness and depressional storage that can decelerate and infiltrate runoff.

3.4 | Nutrient losses

Although previously described differences in runoff were not statistically significant among manure type and the tillage × manure type interaction, differences in nutrient content between the manure types, physical characteristics of the manure, and the presence (or lack) of manure on the soil surface when runoff occurred led to some differences in nutrient (NH_4^+, DRP, TKN, and TP), TS, and VS losses (Tables 2 and 3).

In 2017–2018, NT had up to four times (p = <.01–.03) higher NH_4^+, DRP, TKN, and TP losses than CT, whereas in 2018–2019, only TS, VS, DRP, TKN, and TP losses were three to five times (p = .03–.07) higher in NT than CT. Greater losses from NT are attributed to lower surface storage capacities and subsequent higher runoff volumes and transport capacities than CT (Mueller et al., 1984; Stock, Arriaga, Vadas, Good, et al., 2019; Young & Mutchler, 1976). Despite three times higher runoff volume in 2018–2019, nutrient losses in NT were about half of those from 2017–2018. Although CT also had two times greater runoff in 2018–2019 than in 2017–2018, its nutrient losses were similar to 2017–2018. This might be partly due to the lower (2–15 kg ha^{-1}) nutrients applied in 2018–2019 (Table 1), but nutrient loss differences are likely driven largely by contrasting weather and soil frost conditions in the two study years (Vadas et al., 2019).

Irrespective of tillage type, application of manure (solid or liquid) on snowpack significantly elevated nutrient losses in runoff compared with unmanured control (Tables 2 and 3). In 2017–2018, solid manure treatment had 4–12 times greater nutrient losses than the unmanured control ($p \leq .01$). Similarly, liquid manure treatment had 2–10 times greater NH_4^+, DRP, and TKN losses than the unmanured control (p = <.01–.04). In 2018–2019, solid manure treatment NH_4^+, DRP, and TP losses and liquid manure treatment DRP, TKN, and TP losses were up to 13 times greater than the unmanured control (p = <.01–.05). In 2017–2018, liquid manure applied had 45 and 47% higher TN and TP contents ($p < .01$) than solid manure, respectively, whereas in 2018–2019, only the TN (45%) content of liquid manure was higher ($p < .01$) than solid manure. Despite considerable differences in nutrient content, no significant runoff nutrient losses were observed between liquid and solid manure treatments. This may be influenced by similar runoff depths between liquid and solid manure treatments (Table 2) and emphasizes that, without sufficient runoff to mobilize nutrients, higher losses are not solely a result of higher nutrient content (Vadas et al., 2019). In both years of the study, liquid manure accumulated in snowpack was readily lost with snowmelt, whereas solid manure did not wash away with runoff but remained on the surface, allowing for potential nutrient release each time it interacted with runoff water. After its application, the solid manure was present on the surface until the summer planting (Supplemental Figure S1).

Tillage-influenced runoff and manure type characteristics led to differences between tillage × manure type treatments (Table 2). In 2017–2018, NH_4^+, DRP, and TKN losses from NT–liquid manure and NT–solid manure were four to eight times and three to six times greater ($p < .01$) than CT–liquid manure and CT–solid manure treatments, respectively. During 2018–2019, no effect of tillage × manure type was observed on nutrient losses despite double the runoff depths compared with 2017–2018 (Table 3). As previously explained, greater losses from NT treatments (liquid and solid manure) than CT were driven by greater runoff volumes and their capacity to mobilize nutrients (Vadas et al., 2018). The lower losses in CT–liquid manure than other treatments can be attributed to the physical form of liquid manure combined with the depressional storage capacity of CT likely allowing nutrients to infiltrate into the soil along with snowmelt and rain-on-snow. Although not always statistically significant (p = <.01–.32), others have observed similar fall tillage benefits in reducing wintertime nutrient losses compared with NT at the plot (Stock, Arriaga, Vadas, Good, et al., 2019) and field (Zopp et al., 2019) scales.

Overall, interannual variability and differences between treatments indicate complex interactions of manure characteristics and field conditions partly influenced by tillage and environment as drivers of nutrient losses (Azmatch et al., 2012; Stock, Arriaga, Vadas, Good, et al., 2019). In dairy agroecosystems, winter manure application, such as in this study, elevates the nutrient losses in winter runoff irrespective of manure type. The magnitude of losses depends upon complex soil conditions (surface storage capacity, soil moisture, and frost), manure characteristics, and distribution of runoff across the winter. This complexity challenges effective manure management strategies and indicates a need for long-term experiments and modeling to understand the dynamic nature and variability of wintertime hydrology.

3.5 | Normalized nutrient losses

Nutrient losses were normalized in an attempt to remove variability introduced by differences in total nutrients added with liquid and solid manure and to more directly compare the losses. In 2017–2018, except for TP, tillage × manure type had a significant effect on normalized nutrient losses (Figure 2a). In 2018–2019, no significant differences were observed between tillage × manure type treatments (Figure 2b). During the 2017–2018 winter season, NT-solid manure exported 45, 27, and 105 g of NH_4^+, DRP, and TKN nutrients, respectively, for every kilogram of TN or TP applied, and the normalized loads were 2–64 times greater than the other treatments (NT–liquid manure, CT–liquid manure, and CT–solid manure) (Figure 2a). The higher losses from NT–solid manure can be attributed to NT ability to produce higher runoff volumes and physical characteristics of solid manure (>20% solids) and its potential to release nutrients over each time it interacts with runoff.

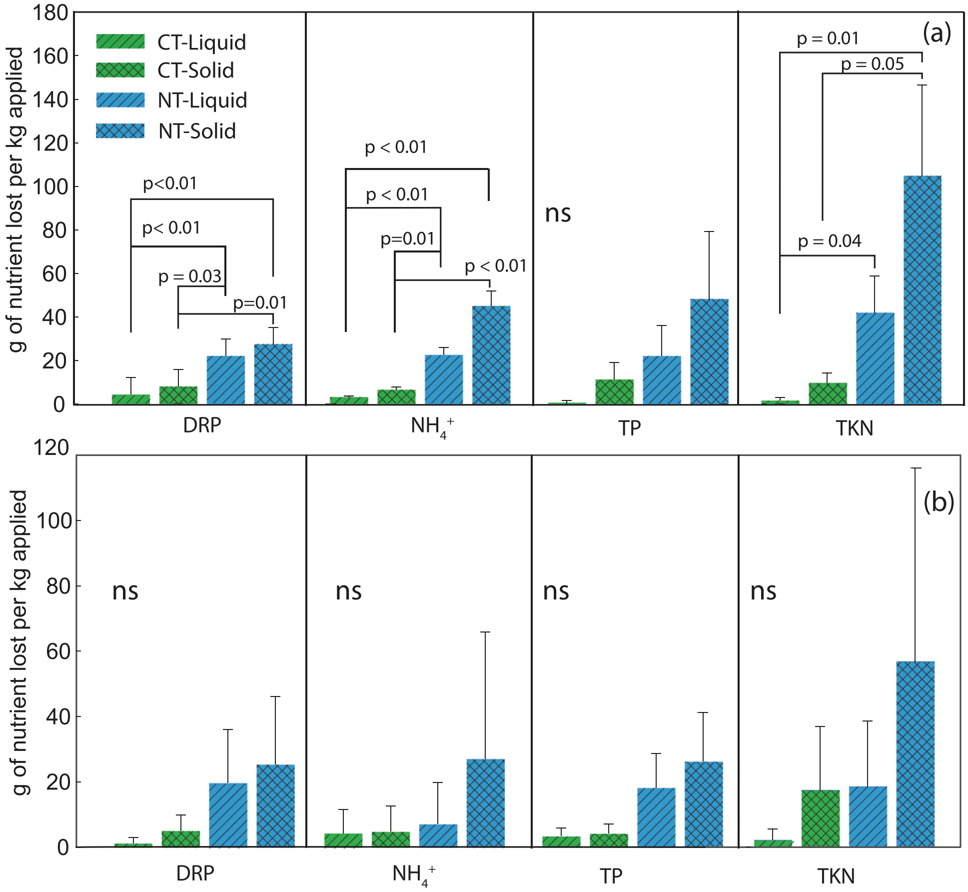

FIGURE 2 Normalized seasonal N and P loads (± SE) by tillage × manure type during the (a) 2017–2018 and (b) 2018–2019 monitoring seasons. All bars present grams of nutrient lost per kilogram of total N or P applied through manure. *p* values within a nutrient category indicate statistically significant differences among treatments at the .1 probability level (ns, not statistically significant difference among the treatments within a nutrient category). CT, chisel tillage; DRP, dissolved reactive P; NT, no-tillage; TKN, total Kjeldahl N; TP, total P

Solid manure can behave similarly to a slow-release fertilizer, especially when applied on frozen agricultural fields with no active crop (for nutrient uptake) and minimal soil microbial activity (for decomposition). Although nutrient release characteristics of solid manure were not measured, depending on environmental conditions, solid manure can remain frozen after its application, restricting its nutrient release. In a laboratory study, Williams et al. (2011) found that manure remained frozen when applied on frozen soil (below the snowpack) and was less susceptible to P losses. Also, during winter, solid manure needs a medium (water) to release and transport its nutrients (runoff and infiltration), and liquid manure, because of its physical state (<5% solids), can be easily lost and infiltrated without a medium. As discussed previously, despite five to seven runoff events during the study years, solid manure applied on snowpack did not wash away completely with runoff but remained on the surface, allowing for potential nutrient release each time it interacted with runoff. In a laboratory study, Vadas et al. (2018) observed that liquid manure (4.6% solids) applied on snowpack (1,400 ml of water equivalent; without soil) had complete interaction with snowmelt and released more DRP and NH_4^+ than semi-solid manure (11.6–12.6% solids), which had incomplete interaction with snowmelt (1,250 ml). Similarly, in modeling field-scale runoff, Vadas et al. (2017) found that only 20% of snowmelt water interacted with solid beef manure.

The normalized nutrient losses combined with our field observations support that solid manure releases nutrients slowly depending on the runoff volume it interacts with each time. Overall, irrespective of tillage type, solid manure is prone to nutrient losses for longer periods and may have higher cumulative losses than liquid manure during winters. However, soil conditions (frost, surface storage, and infiltration capacities) and environmental conditions (snowmelt and rain-on-snow volume) during runoff events play an important role in differentiating the losses between tillage and manure type managements.

4 | CONCLUSIONS

In cold-region corn silage systems (lack residue), both tillage management and winter manure application on snow-covered frozen soil can influence wintertime runoff and nutrient losses. In this study, fall CT created depressions on the surface and significantly reduced runoff compared with NT by providing more opportunity for infiltration. However, such tillage operations may risk erosion, especially during non-winter periods. Therefore, tradeoffs must be quantified between winter and non-winter periods, or increased risk of erosion must be mitigated before making tillage management decisions. Irrespective of CT or NT, liquid and solid manure applied significantly elevated runoff nutrient losses (NH_4^+, DRP, TKN, and TP) up to 11 times (average of two seasons) compared with unmanured control. Solid manure (>20% solids) applied can remain on the soil surface, whereas liquid manure (<5% solids) can infiltrate into soil depending on the surface (depressions) and subsurface (soil frost, infiltration potential) conditions. Overall, on CT and NT surfaces, applying liquid manure will be more beneficial than solid manure. However, targeting applications on non-frozen ground (before the onset of snow) might be more beneficial for soil and water quality. Finally, additional research that investigates manure type application rates and timing in different soils and weather conditions would help establish robust recommendations for livestock farmers to strategize manure type collection and land applications.

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AUTHOR CONTRIBUTIONS

Laxmi R. Prasad: Data curation; Formal analysis; Investigation; Methodology; Project administration; Software; Validation; Visualization; Writing – original draft; Writing – review & editing. Anita M. Thompson: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing – review & editing. Francisco J. Arriaga: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Supervision; Validation; Visualization; Writing – review & editing. Peter A. Vadas: Conceptualization; Data curation; Investigation; Methodology; Resources; Validation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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