MANURE APPLICATION UNDER WINTER CONDITIONS: NUTRIENT RUNOFF AND LEACHING LOSSES

M. R. Williams, G. W. Feyereisen, D. B. Beegle, R. D. Shannon, G. J. Folmar, R. B. Bryant

ABSTRACT. *Winter application of manure is commonly practiced in the northeastern and north-central U.S. Potential nutrient losses from winter-applied manure are difficult to predict due to uncertainty in weather forecasting and limited knowledge on soil-nutrient-hydrology interactions during the winter. The objective of this study was to extend the understanding of nutrient cycling and transport processes associated with manure application methods during winter months. Specifically, the influence of manure position within the snowpack on nutrient losses was examined using a laboratory approach. Dairy manure was applied either before, midway through, or upon completion of an artificial snowfall. Runoff and leachate were subsequently collected throughout a snowmelt event and rainfall simulations. Manure application prior to the snowfall increased the losses of total N and NH_4-N in snowmelt runoff and resulted in larger losses of both N and P in runoff during the rainfall simulation. Manure application on top of the snow reduced the amount of NH_4-N losses but increased the losses of organic N, DRP, and total P in snowmelt runoff. The results of this research show that the relative position of manure within the snowpack plays a significant role in the fate of N and P from winter-applied manure.*

Keywords. *Leachate, Lysimeter, Manure, Runoff, Winter.*

Manure and nutrient management continue to be areas of increased focus due to concern over surface water eutrophication and degradation (Boesch et al., 2001; Carpenter et al., 1998; Correll, 1998; Daniel et al., 1998). In recent years, the relative risk of nutrient loss among winter manure application, over-winter storage and large applications in the spring, or alternative spreading options has been debated. USDA-NRCS Nutrient Management Standard 590 requires conservation measures when manure is applied to frozen soils with slopes greater than 9%. Many states have also formulated additional standards for winter manure management. While a few states in the northeast and north-central U.S. prohibit manure application during the winter (fig. 1), manure management guidelines for many states can be summarized as follows: (1) avoid spreading manure on areas that have a high risk for runoff, (2) avoid spreading manure on steep slopes, and (3) avoid spreading manure on fields adjacent to water bodies (Srinivasan et al., 2006). These guidelines are based on the best available knowledge of soil-nutrient-hydrology interactions that affect nutrient losses in runoff to surface-water bodies or movement to groundwater (Srinivasan et al., 2006). However, the available knowledge on nutrient transport and cycling from winter manure spreading is minimal, and current guidelines largely rely on the common sense of the applicator (Fleming and Fraser, 2000).

The potential for nutrient transport from winter-applied manure varies due to infiltration, runoff, erosion, and nutrient cycling processes, which all are sensitive to whether air and soil temperatures are above or below freezing. Consequently, winter nutrient losses are often difficult to predict because the understanding of winter runoff generation is limited and there is a wide range of variation in climatological sequences both within a year and between years (Klausner et al., 1976). Furthermore, it is predicted that climate change will result in more unstable winters with an increased number of freezing and thawing events in northern latitudes (Sinha et al., 2010). The occurrence of more freeze-thaw events combined with more precipitation during the winter months (Kværnø and Øygarden, 2006) will likely affect both nutrient transport and cycling processes.

Studies that have looked at winter application and nutrient losses during snowmelt and thawing conditions differ in methods and scales, but the majority of these studies observed substantial nutrient losses (Srinivasan et al., 2006). Up to 20% of nitrogen, 12% of phosphorus, and 14% of potassium were lost in surface runoff from manure applied to frozen soil in Wisconsin (Hensler et al., 1970). Manure cannot be quickly incorporated into the soil when it is frozen or snow-covered, which increases the risk of nutrient loss in

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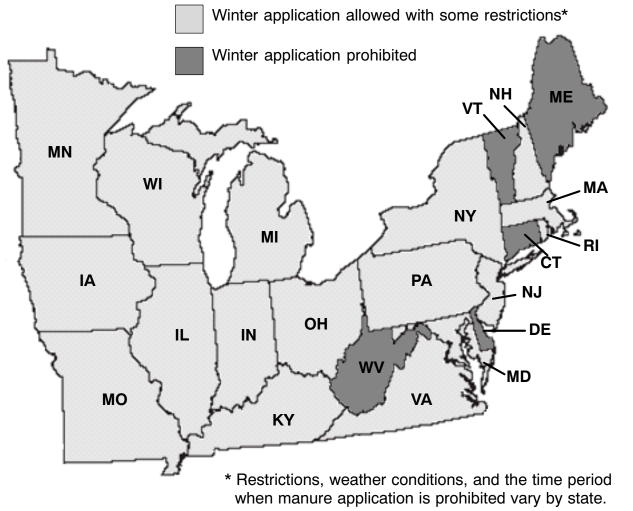


Figure 1. Northeast and north-central U.S. map with winter manure application restrictions.

surface runoff. Therefore, the relative placement of manure with respect to snow has been recognized as an important factor in determining the amount of nutrient loss in surface runoff from winter-applied manure. In two similar studies, manure was applied to a field prior to a snowfall event; however, two different conclusions were reached. Young and Mutchler (1976) reported that when manure was applied and covered with snow, higher concentrations of nutrients in the runoff were seen. Alternatively, Klausner et al. (1976) found that when manure was covered with snow, melting occurred at a later date and nutrient losses were not as great compared to manure applied on top of the snow.

Research has illustrated the complexity of nutrient dynamics in response to a wide array of winter conditions (Srinivasan et al., 2006). As Kongoli and Bland (2002) point out, however, most of the field studies on manure management under winter conditions predate 1980. Furthermore, a process-level understanding of nutrient cycling and transport processes associated with manure application methods during winter months is still lacking. The objective of this research was to extend the understanding of manure nutrient cycling and transport processes under winter conditions. Specifically, the influence of manure position within the snowpack on surface and subsurface losses of N and P was examined using laboratory methods. A laboratory approach was chosen in order to control climatic and environmental variables, which would not be feasible in a field setting. We hypothesized that nutrient losses in surface runoff and subsurface leachate would be less when manure was applied on top of the snow compared to when it was applied to the soil surface and immediately covered with snow.

Materials and Methods

Lysimeter Collection and Laboratory System

The soil thermal cycling system used in this study followed the design described in detail by Williams et al. (2010) and consisted of a 61 cm wide × 61 cm long × 61 cm deep insulated bin containing four 15 cm diameter × 50 cm long lysimeters encased in sand. A commercially available electric resistance heating cable was buried in the sand at the bottom of the bin and created an upward heat flux representative of heat flow under field conditions.

Twenty-four undisturbed soil cores from the Pennsylvania State University's Russell E. Larson Agricultural Research Center (40° 42′ 36″ N, 77° 57′ 55″ W) were collected in February 2009. The soil at the site was Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf), and the surface was covered with corn residue at the time of collection. Each core was collected by driving a 15 cm diameter × 50 cm long schedule 80 PVC pipe into the soil between two rows of corn stubble with a 1.1 Mg drop hammer. The lysimeters were excavated by hand, and a 15 cm diameter, schedule 40 PVC end cap was pushed over the bottom end of the lysimeter. The PVC end cap contained a tapped 1.25 cm diameter hole to which a leachate collection system was attached. Additionally, in order to suppress sidewall bypass flow during subsequent snowmelt and rainfall simulation testing, the lysimeters were built after the design of Feyereisen and Folmar (2009). PVC spacers cut from SDR 35 pipe (0.5 cm thick), designed to provide a gap between the soil core and the lysimeter wall, were in place during insertion of the lysimeter into the soil (fig. 2). The spacers were subsequently removed, and the resultant space was backfilled with liquefied petroleum jelly. The petroleum jelly created a watertight seal between the soil column and the lysimeter wall. A 1.6 cm diameter hole was then drilled into the lysimeter wall at or slightly below the soil surface, and a surface runoff collection system was attached.

The lysimeters were randomly divided into six groups of four, and each group was placed in a pre-constructed 61 cm × 61 cm × 61 cm steel bin. Each steel bin had a 2 cm thick perforated plywood bottom with extruded polystyrene insulation (7.5 cm thick, R-value = 15) on top of the plywood. The walls of the bin were also encased with extruded polystyrene insulation (2.5 cm thick, R-value = 5) that extended 15 cm above the top of the bin. The heat source consisted of a commercially available heating cable (Orbit Radiant Heating, Perkasie, Pa.) that was placed in two layers, 2.5 and 7.6 cm, above the insulation on the bottom of each bin. Masonry sand was carefully added and packed over the heating cable and around the lysimeters until the bins were filled up to the soil surface. One lysimeter from each bin was fitted with four type-T thermocouples (Culik et al., 1982) at 5, 10, 20, and 30 cm depths below the soil surface. The thermocouples along with two thermistors and an electronic relay that controlled the heating cable were connected to a Campbell Scientific CR10X datalogger, which was programmed to maintain a set temperature at the 40 cm depth.

Artificial Snowfall and Rainfall Simulation

The lysimeter-bin assemblies were placed on custom-built carts, and water was added to the soil from the bottom using a reverse wetting process. The lysimeters were allowed to drain until they were all at field capacity. They were then pushed into a walk-in freezer (Leer ICE Merchandisers, New Lisbon, Wisc.) and were subjected to an air temperature of -4°C. The soil froze downward from the surface, and the heating cable was used to maintain a temperature of 1.1°C at a depth of 40 cm. In order to compare nutrient losses in runoff and leachate from winter-applied manure, each of the bins was defined as one of six treatments: unmanured control (C), unmanured snow-covered control (SC), manure on frozen soil (MF), manure on top of snow (MTS), manure between

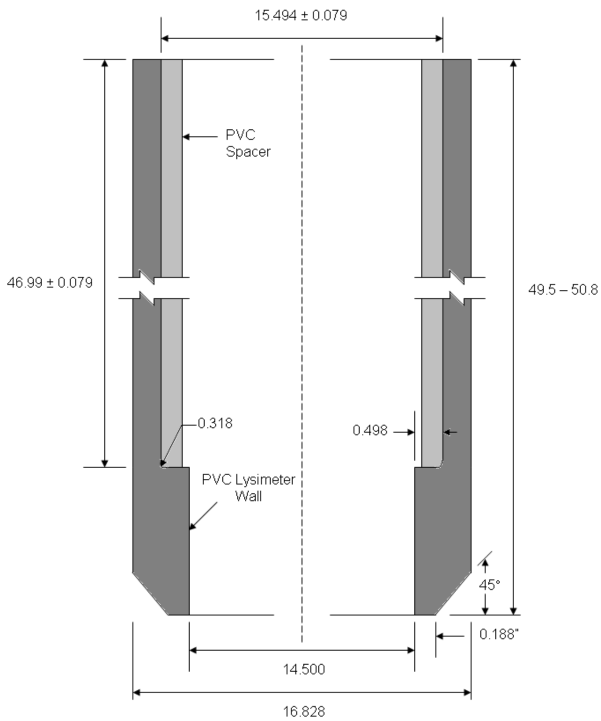


Figure 2. Schematic of a lysimeter (dimensions are in cm)

Table 1. Manure analysis.

Solids (%)	pH	NH_4-N[a]	Organic N[a]	Total N[a]	Total P_2O_5[a]
9.7	8.3	2.77	3.28	6.05	2.55

[a] Values are in kg 1000 L^{-1}.

snow (MBS), and manure under snow (MUS). After three days, the SC, MTS, MBS, and MUS treatments were pulled out of the freezer and subjected to an artificial snowfall event. Dairy manure was applied either before, midway through, or upon completion of the snowfall event (table 1). The fourth bin did not receive a manure application and served as the SC treatment. One of the two bins remaining in the freezer received a manure application and represented manure applied directly to frozen soil (MF), while the other served as an unmanured control (C).

The manure was applied at a rate of 3.74 g cm^{-2} over a 413 cm^2 area, which was equivalent to an application rate of 37,400 L ha^{-1} (4000 gal ac^{-1}). The application rate was predetermined based on a manure analysis (table 1) and a recommendation of 225 kg total N ha^{-1}. The snowfall took place over a 3 h period during which 7.5 cm of snow accumulated on top of the bins. The snow was created using a Blizzard Sno-Wand (Snowstation, LLC, Natick, Mass.) in conjunction with an air compressor and pressure washer. The ambient air temperature was approximately -5°C throughout the snowmaking process. A snow fence was built to reduce wind speeds and ensure that the snow fell evenly on the lysimeter-bin assemblies. The artificial snow had a snow-water equivalent (i.e., the amount of water contained in the snowpack) of 2.89 cm and a snow-water density (i.e., the depth of water in the snowpack divided by the depth of the snow) of 0.38.

The bins were placed back in the freezer and maintained at an air temperature of -4°C in order to prevent melting of the snow. After a 5-day period, all of the bins were moved outside into an open area to receive direct sun and to allow the snow to melt. The snow completely melted after four days (March 20 to 23), and the bins were returned to the freezer and maintained above freezing at an air temperature of 2°C. Following another 5-day period in the freezer, the bins were individually subjected to a rainfall simulation. The rainfall simulations were conducted using a modified protocol of Sharpley et al. (2001). A single nozzle (FullJet 1/2 HH SS 14WSQ, Spraying Systems Co., Wheaton, Ill.) was attached to a frame at a height of 3.05 m above the top of the bins. The simulation duration was 1 h at an average intensity of 2.5 cm h^{-1}. The uniformity coefficient of the individual rainfall simulations ranged from 0.94 to 0.99. The uniformity coefficient was determined by measuring rainfall for 15 min immediately following each rainfall simulation in four 15 cm diameter cups placed on top of the lysimeters in the bin. The 24 values (4 lysimeters × 6 simulations) from the individual simulations were then combined to calculate the uniformity coefficient among treatments, which equaled 0.95. Following the rainfall simulations, the lysimeter-bin assemblies were returned to the freezer and maintained at an air temperature of 2°C.

Runoff and Leachate Water Samples

During both the snowmelt and rainfall simulations, surface runoff and subsurface leachate were collected. Samples were collected every 100 mL of runoff or leachate, and the time of collection was recorded. Samples were refrigerated immediately after collection until analysis. Dissolved reactive phosphorus (DRP), ammonium-nitrogen (NH_4-N), and nitrate-nitrogen (NO_3-N) were determined colorimetrically on 0.45 μm filtered runoff and leachate water. Total nitrogen (total N) was measured on unfiltered water samples by digesting the sample using alkaline persulfate digestion, thereby converting all N forms to NO_3-N. Total N (as NO_3-N) was determined using a Lachat autoanalyzer (Quik Chem Methods FIA+ 8000 Series, Lachat Instruments, Loveland, Colo.). Unfiltered samples were also analyzed for total phosphorus (total P) by using an aqua regia digest and ICP spectrometry. Nutrient losses were then calculated by multiplying the concentration of the nutrient by the volume of the sample and dividing by the surface area of the lysimeter. Organic nitrogen (organic N) losses were calculated as the difference between total N and NH_4-N losses.

Soil Samples

When the lysimeters were collected, soil samples were taken adjacent to the outside of the lysimeter wall. The soil was sampled from 0 to 15 cm deep. The samples were used to establish a baseline for the amount of nutrients in the soil prior to manure application. At the conclusion of the study (approximately four weeks after the rainfall simulations were completed), the manure remaining on the soil surface was removed and soil samples were collected from within the lysimeter from 0 to 15 cm deep. All soil samples were air dried, sieved (2 mm), and analyzed for water-extractable phosphorus (WEP) by shaking 2.0 g of soil with 25 mL of deionized water for 1 h. Phosphorus in the extracts was measured by ICP spectrometry. Inorganic nitrogen (NH_4-N and NO_3-N) in the soil samples was determined by flow injection analysis of 2 M KCl extracts (Quik Chem Methods FIA+ 8000 Series, Lachat Instruments, Loveland, Colo.). The final and initial soil samples were then compared to calculate the nutrient level change, thus determining the nutrients that would remain in the soil for potential crop use in the spring.

Statistical Analysis

Runoff, leachate, and soil data were analyzed to assess trends related to the manure application location with respect to snow cover. The data were evaluated by ANOVA using the general linear models procedure with SAS version 9.1 (SAS, 2002). Pairwise comparisons were made using Tukey's Studentized range (HSD) test in order to separate treatment means. Differences discussed in the text were significant at $\alpha = 0.05$.

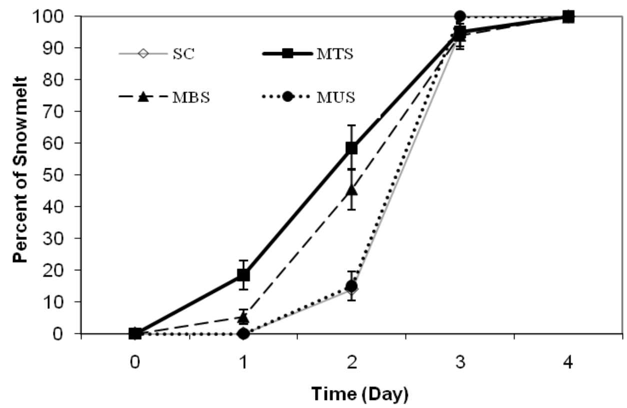


Figure 4. Percentage of snow that melted per day during the 4-day snowmelt event. Error bars represent one standard deviation.

Results and Discussion

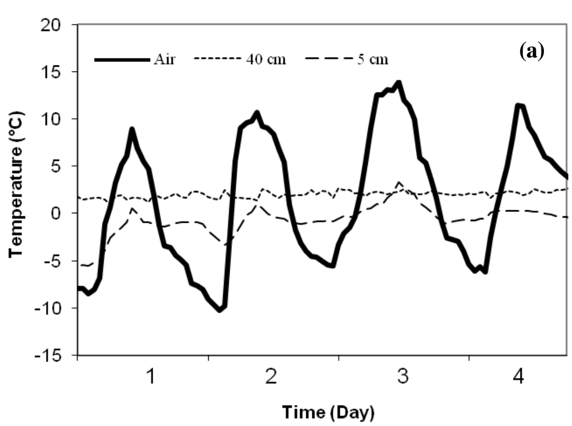
Snowmelt Hydrology

The soil remained frozen at a depth of 5 cm until the third day of the snowmelt (fig. 3a). As a result, infiltration was limited, and the melting snow became surface runoff. Under the prevailing conditions, the decrease in infiltration created by the frozen soil resulted in an average of 78% of the snowmelt water becoming surface runoff (data not shown). The decrease in infiltration was uniform across all treatments with snow and did not vary based on manure position with respect to snow or between manured and non-manured treatments (fig. 3b). Previous research has shown that high soil moisture contents at the time of soil freezing can significantly decrease the final infiltration rate (Zuzel and Pikul, 1987); therefore, the field capacity moisture condition for all treatments at the onset of the experiment was likely the main factor that influenced the volume of surface runoff.

While the surface runoff volumes were similar among treatments with snow, the placement of the manure impacted both the timing and rate of snowmelt (fig. 4). When the manure was applied on top of the snow, the manure decreased the surface albedo (Kongoli and Bland, 2002) and increased the temperature at the snow-manure interface, thereby promoting earlier melting compared to the MUS and SC treatments (fig. 4). At the end of the second day of the snowmelt, 60% of the snow had melted when the manure had been applied on top of the snow, while significantly less (15%) melted when there was no manure or when it had been applied prior to the snowfall. The percentage of snow that melted for the MBS treatment over the 2-day period was not significantly different from the MTS treatment. On day 3, however, a shift occurred in the manure's influence on the snowmelt hydrology. The MTS treatment acted as an insulator and retarded the melting rate (Kongoli and Bland, 2002) compared to that of the MUS or SC treatments. An average of 80% and 85% of the snow melted on the third day for the MUS and SC treatments, respectively (fig. 4). The rapid rate of melting on day 3 resulted in an average melting rate between days 1 and 3 for the MUS and SC treatments that was significantly greater than the melting rate of the MTS treatment over those two days.

Rainfall Simulation Hydrology

The soil was just above freezing (2°C) at the time of the rainfall simulations; therefore, the water leaving the lysimeters was in the form of both surface runoff and subsurface leachate. The addition of snow to the SC, MTS, MBS, and MUS treatments did not have a significant impact on the amount of runoff or leachate during the rainfall simulation compared to the non-snow treatments (data not shown). Conversely, the presence of manure significantly impacted the amount of runoff and leachate. On average, 60% of the precipitation became surface runoff for the treatments with manure, while significantly less (38%) precipitation became surface runoff for the non-manured treatments (fig. 5b). This trend is contradictory to previous research, which noted significantly



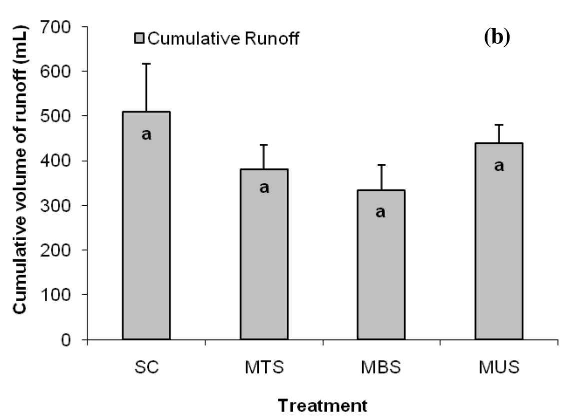


Figure 3. (a) Temperatures of air and soil (40 and 5 cm depths) and (b) cumulative runoff volume from the snowmelt event (error bars represent one standard deviation, bars with the same letter are not statistically different at α = 0.05).

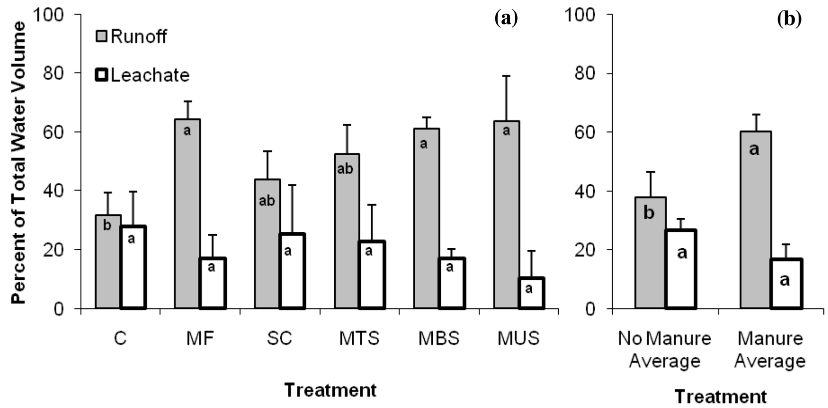


Figure 5. Runoff and leachate as percentages of the total rainfall volumes applied during the rainfall simulations: (a) average runoff and leachate for each treatment, and (b) runoff and leachate comparison between manured and non-manured treatments. Error bars represent one standard deviation. Bars in each figure and within each category (runoff and leachate) with the same letter are not statistically different at α = 0.05.

lower runoff and erosion from manured plots as compared to non-manured plots (Kongoli and Bland, 2002; Converse et al., 1976; van Vliet et al., 2002). In Minnesota, Young and Holt (1977) found that manure application appreciably reduced soil loss and surface runoff. The observed reduction in runoff and erosion was attributed to the mulching effect of the manure.

In the current study, although a mulching effect was observed, it did not lead to significant differences in runoff or leachate volumes among the treatments with manure (fig. 5a). The small surface area of the lysimeters used in this study may not have had the capacity to fully demonstrate the extent of the mulching effect of the manure during the subsequent rainfall event. When the manure was applied on top of the snow, it was not spread uniformly across the entire snow surface. The non-uniform application created areas with and without manure, which resulted in differences in snow melting rates. Differences in melting rate, in turn, resulted in the mulching of the manure as the snow melted. The mulching resulted in the MTS treatment having 10% less surface runoff and 12% more leachate than the MUS treatment during the rainfall simulation (fig. 5a). In the MUS treatment, the manure remained as a flat, hardened sheet that covered the soil surface, thereby inhibiting infiltration and increasing surface runoff. It is hypothesized that in a larger plot- or field-scale study, the manured treatments would have higher rates of infiltration than the non-manured treatments. Additionally, the mulched manure derived from a manure application on top of snow may further increase infiltration during subsequent rainfall events compared to when it was applied prior to a snowfall.

Snowmelt Nitrogen and Phosphorus Trends

Total N, organic N, and NH_4-N concentrations and losses in surface runoff were significantly different among manure and snow treatments (table 2). The MUS treatment had significantly larger concentrations and losses of NH_4-N compared to the other manure placement locations. NH_4-N losses of 76.4, 114, and 205 μg cm^{-2} were observed for the MTS, MBS, and MUS treatments, respectively. Similarly, total N losses of 255, 231, and 362 μg cm^{-2} were observed for the MTS, MBS, and MUS treatments, respectively, in which the MUS treatment was significantly different from the other manure locations. The organic N losses, however, were higher for the MTS treatment (178 μg cm^{-2}) compared to the MUS (157 μg cm^{-2}) and MBS (117 μg cm^{-2}) treatments. The losses from the MUS, MBS, and MTS treatments represented 21%, 11%, and 8% of NH_4-N; 9%, 12%, and 14% of organic N; and 16%, 10%, and 11% of total N, respectively, of the original manurial nitrogen that was applied (data not shown).

The concentrations and losses of both DRP and total P followed a trend similar to organic N in which the MTS treatment had the largest losses compared to the other manure placement locations (table 2). The DRP losses for the MTS, MBS, and MUS treatments were 2.4, 1.5, and 0.7 μg cm^{-2}, respectively. Similarly, the DRP concentration in surface runoff was significantly larger for the MTS treatment compared to the MUS treatment. Total P losses of 10.9 and 9.1 μg cm^{-2} were observed for the MTS and MUS treatments, respectively, while concentrations of 11.8 and 8.7 μg mL^{-1} were seen. The losses represented 5.6%, 5.2%, and 6.7% of the original manurial total P that was applied to the MUS, MBS, and MTS treatments, respectively (data not shown). The losses of both N and P observed in this study are similar to those reported by Hensler et al. (1970).

The differences in losses and concentrations of organic N, DRP, and total P among the MTS, MBS, and MUS treatments were likely due to the differences in snow melting patterns based on the location of the manure with respect to the snow. The earlier melting date and position of the manure in the MTS treatment caused observable rutting of the snowpack (Klausner et al., 1976) and some mulching of the manure. As the manure was mulched, additional particles and nutrients were detached and more easily transported via surface runoff in channelized flow paths. This is contradictory to a previous study, which noted that snowmelt runoff water generally comes from the underside of the snowpack and travels along the soil surface; therefore, manure applied under the snow would then be in direct contact with the meltwater, resulting in higher concentrations of nutrients in the runoff (Young and Mutchler, 1976). The discrepancy between studies may be due to varying pre-snowfall and pre-melt environmental conditions. In the current study, the manure was applied on frozen soil, immediately covered with a thin snowpack, and the air temperature remained below freezing until the start of the melt. The manure under the snow, therefore, remained frozen and intact throughout the melting process, thus reducing susceptibility to nutrient loss. If the soil had been unfro-

Table 2. Nitrogen and phosphorus losses and concentrations in surface runoff during snowmelt.[a]

Treatment	Loss (µg cm^{-2})		Concentration (µg mL^{-1})	
	NH_4-N	Total N	NH_4-N	Total N
Control (C)	n/a	n/a	n/a	n/a
Manure on frozen soil (MF)	n/a	n/a	n/a	n/a
Snow-covered control (SC)	0.8 ±0.3 c	3.6 ±1.2 c	0.5 ±0.2 d	2.5 ±0.6 c
Manure on top of snow (MTS)	76.4 ±22.1 b	254.5 ±14.8 b	83.0 ±25.8 c	275.6 ±18.7 b
Manure between snow (MBS)	113.8 ±46.1 b	230.6 ±56.8 b	136.4 ±35.0 b	285.3 ±45.2 ab
Manure under snow (MUS)	205.3 ±36.6 a	362.4 ±66.5 a	193.5 ±37.6 a	362.4 ±33.0 a
	DRP	Total P	DRP	Total P
Control (C)	n/a	n/a	n/a	n/a
Manure on frozen soil (MF)	n/a	n/a	n/a	n/a
Snow-covered control (SC)	0.1 ±0.1 c	2.2 ±0.8 c	0.1 ±0.0 b	1.4 ±0.1 c
Manure on top of snow (MTS)	2.4 ±0.7 a	10.9 ±0.8 a	2.6 ±0.8 a	11.8 ±1.1 a
Manure between snow (MBS)	1.5 ±0.6 ab	8.5 ±1.5 b	1.5 ±0.1 a	10.6 ±0.9 a
Manure under snow (MUS)	0.7 ±0.2 bc	9.1 ±1.5 ab	0.6 ±0.2 b	8.7 ±1.2 b

[a] Values are means ± standard deviation. Means within a column followed by the same letter are not different at α = 0.05 (n/a = not applicable).

en or if the snowpack had been deeper, the manure may have remained thawed and more vulnerable to nutrient loss. The influence of soil temperature on nutrient losses from winter-applied manure should be investigated in future research.

The significantly smaller NH_4-N losses and concentrations in the surface runoff from the MTS treatment compared to the MUS treatment suggest that ammonia volatilization also played a role in the amount of N lost. Historically, ammonia volatilization was assumed to be negligible during the winter due to cooler air temperatures. Although volatilization losses were not measured in this study, the trends of the other nutrient analytes imply that NH_4-N losses in surface runoff from the MTS treatment should have been equal to or larger than those observed for the MUS treatment if volatilization was not occurring. It is well documented in previous research that the amount of NH_4-N in the runoff water is dependent on the amount of ammonia volatilization between the time of manure spreading and the first runoff event (e.g., Steenhuis et al., 1981). Furthermore, when manure is spread and covered immediately with snow, the potential for atmospheric losses of N are minimal (Lauer et al., 1976). During non-winter periods, manure is often incorporated into the soil in order to reduce ammonia volatilization because incorporation allows the ammonia gas to be trapped in the soil and converted back into NH_4-N. It is likely that a similar process may occur when manure is applied and covered with snow. The ammonia gas may be trapped within the snowpack and subsequently reconverted back into NH_4-N. The main difference between winter and non-winter periods, however, is that during the winter, when the snow melts and infiltration is limited due to frozen soil, the NH_4-N easily could be transported in surface runoff. Therefore, NH_4-N contamination of surface-water bodies may be reduced when the manure is applied on top of the snow; however, potential air quality concerns may arise as a result of increased ammonia volatilization compared to when it is applied prior to snowfall.

Rainfall Simulation Nitrogen and Phosphorus Trends

The MF treatment had the largest concentrations and losses of both NH_4-N and total N during the rainfall simulation compared to the other manure treatments (table 3). Losses of NH_4-N and total N for the MF treatment were 8.9 and 39.2 µg cm^{-2}, respectively, while the average concentrations were 24.4 and 107 µg mL^{-1}. Although the treatments that had both manure and snow did not have significantly different NH_4-N and total N losses during the rainfall simulation, the trends observed were similar to that of the snowmelt runoff event (table 3).

The MTS treatment had the largest losses of DRP and total P during the snowmelt; however, the MUS treatment had sig-

Table 3. Nitrogen and phosphorus losses and concentrations in surface runoff during rainfall simulation.[a]

Treatment	Loss (µg cm^{-2})		Concentration (µg mL^{-1})	
	NH_4-N	Total N	NH_4-N	Total N
Control (C)	0.9 ±0.4 b	4.3 ±1.3 b	2.0 ±0.6 c	9.7 ±1.3 b
Manure on frozen soil (MF)	8.9 ±7.1 a	39.2 ±33.1 a	24.4 ±3.8 a	106.6 ±19.1 a
Snow-covered control (SC)	0.8 ±0.3 b	7.5 ±5.4 b	0.6 ±0.5 c	10.8 ±2.4 b
Manure on top of snow (MTS)	3.3 ±1.6 ab	12.1 ±4.6 ab	5.2 ±2.3 bc	18.7 ±5.1 b
Manure between snow (MBS)	2.7 ±0.5 ab	11.1 ±1.3 ab	3.9 ±0.7 bc	15.7 ±1.0 b
Manure under snow (MUS)	5.9 ±2.7 ab	18.3 ±5.1 ab	8.1 ±2.5 b	25.5 ±5.0 b
	DRP	Total P	DRP	Total P
Control (C)	0.1 ±0.1 d	0.8 ±0.2 b	0.2 ±0.1 d	1.8 ±0.2 d
Manure on frozen soil (MF)	1.0 ±0.7 bc	4.0 ±2.9 ab	2.9 ±0.4 b	11.5 ±0.7 a
Snow-covered control (SC)	0.1 ±0.1 cd	1.6 ±1.1 ab	0.2 ±0.1 d	2.4 ±0.8 d
Manure on top of snow (MTS)	1.1 ±0.3 bc	2.9 ±0.7 ab	1.8 ±0.4 c	4.5 ±0.5 c
Manure between snow (MBS)	1.2 ±0.3 b	2.8 ±0.3 ab	1.7 ±0.3 c	4.3 ±0.6 c
Manure under snow (MUS)	2.8 ±0.7 a	4.5 ±1.3 a	3.8 ±0.4 a	6.1 ±0.6 b

[a] Values are means ± standard deviation. Means within a column followed by the same letter are not different at α = 0.05.

nificantly higher losses during the rainfall simulation (table 3). Dissolved reactive phosphorus losses of 2.8, 1.1, and 1.0 μg cm^{-2} were observed for the MUS, MTS, and MF treatments, respectively. Dissolved reactive phosphorus concentrations in surface runoff were also significantly higher for the MUS treatment compared to the other treatments. Total P losses were not significantly different among treatments, but the MF treatment had a significantly higher total P concentration compared to the other manured treatments.

Nitrogen and P losses in the subsurface leachate during the rainfall simulation were very inconsistent due to the natural variability of the soil. For all of the treatments, NH_4-N concentrations averaged 0.0 to 0.7 μg mL^{-1}. The low concentrations were expected, since NH_4-N is typically adsorbed to the surface of soil particles. When macropores were present, as evident by large leachate volumes, NH_4-N concentrations from the MF treatment reached 2.5 μg mL^{-1}. Nitrate-nitrogen was present in the leachate, but there were no significant differences among the treatments with manure. Average concentrations of NO_3-N ranged from 0.9 to 2.2 μg mL^{-1} for the treatments with manure. There was, however, a significant difference between treatments with and without manure, as those without manure had an average NO_3-N concentration of only 0.6 μg mL^{-1}. When macropores were present, the manure on frozen soil (MF) treatment had a peak NO_3-N concentration of 4.8 μg mL^{-1}, whereas the control had a peak of only 1.6 μg mL^{-1}. The DRP and total P concentrations were very small and averaged 0.5 μg mL^{-1} or less for all of the treatments. When macropore flow was present, DRP concentration reached a maximum of 1.1 μg mL^{-1} from the MF treatment.

Soil Nutrient Levels

Soil NH_4-N, NO_3-N, and WEP levels pre- and post-manure application are shown in table 4. The initial concentrations of NH_4-N, NO_3-N, and WEP for each treatment were not significantly different prior to the manure application and averaged 6.6, 4.1, and 3.5 mg kg^{-1}, respectively (table 4). Following the snowmelt and rainfall simulations, WEP concentrations decreased for the treatments with no manure to 2.9 mg kg^{-1} and increased to 4.3, 4.5, and 3.7 mg kg^{-1} for the MTS, MBS, and MUS treatments, respectively (table 4). While the addition of manure to the soil increased the concentration of WEP in the soil, the placement of the manure with respect to snow did not significantly impact the final concentrations. The P losses during the snowmelt were largest for the MTS treatment. Conversely, the P losses were larger from the MUS treatment during the rainfall simulation. The cumulative losses of DRP from the snowmelt and rainfall simulation were nearly identical for the treatments with both manure and snow (table 5). The MTS, MBS, and MUS treatments had average cumulative DRP losses of 3.5, 2.7, and 3.5 μg cm^{-2}, respectively. Therefore, the resulting concentrations of WEP in soil reflected the similar cumulative losses of P (table 5).

The NH_4-N concentrations decreased for every treatment following the snowmelt and rainfall simulations (table 4). The only significant difference was between the MBS treat-

Table 4. Extractable soil nutrient levels before (initial) and after (final) manure application and subsequent snowmelt event and rainfall simulation.[a]

Treatment	NH_4-N (mg kg^{-1})		NO_3-N (mg kg^{-1})		WEP (mg kg^{-1})	
	Initial	Final	Initial	Final	Initial	Final
Control (C)	7.0 ±0.9 a	3.8 ±0.3 b	3.8 ±0.4 a	6.8 ±1.1 c	3.5 ±0.1 a	2.9 ±0.3 b
Manure on frozen soil (MF)	6.7 ±1.3 a	3.7 ±0.6 b	4.5 ±1.5 a	17.9 ±3.9 a	3.3 ±0.1 a	3.9 ±0.5 a
Snow-covered control (SC)	6.0 ±0.6 a	3.5 ±0.7 b	4.7 ±1.6 a	7.1 ±1.7 c	3.5 ±0.1 a	2.9 ±0.3 b
Manure on top of snow (MTS)	6.2 ±1.9 a	3.4 ±0.5 b	3.9 ±1.1 a	8.2 ±1.1 c	3.6 ±0.3 a	4.3 ±0.6 a
Manure between snow (MBS)	7.5 ±1.4 a	5.3 ±0.4 a	3.2 ±0.2 a	11.3 ±1.7 b	3.5 ±0.5 a	4.5 ±0.7 a
Manure under snow (MUS)	6.4 ±0.5 a	3.9 ±0.4 b	4.7 ±1.5 a	7.7 ±0.7 c	3.6 ±0.4 a	3.7 ±0.5 ab

[a] Values are means ± standard deviation. Means within a column followed by the same letter are not different at $\alpha = 0.05$.

Table 5. Summary of nutrient losses in surface runoff and subsurface leachate and changes in extractable soil nutrient levels.[a]

Treatment	Runoff and Leachate Losses (μg cm^{-2}) NH_4-N		NO_3-N		Change in Soil Nutrients (mg kg^{-1})	
	Snowmelt	Rainfall[b]	Snowmelt	Rainfall[b]	Δ NH_4-N	Δ NO_3-N
Control (C)	n/a	0.9 ±0.4	n/a	0.5 ±0.1	-3.2 ±1.0	3.0 ±1.2
Manure on frozen soil (MF)	n/a	8.9 ±7.1	n/a	0.4 ±0.3	-3.0 ±1.4	14.1 ±3.5
Snow-covered control (SC)	0.8 ±0.3	0.8 ±0.3	<0.1	0.3 ±0.6	-2.5 ±1.1	2.4 ±0.4
Manure on top of snow (MTS)	76.4 ±22.1	3.3 ±1.6	<0.1	0.3 ±0.3	-2.8 ±2.2	4.4 ±1.2
Manure between snow (MBS)	113.8 ±46.1	2.7 ±0.5	<0.1	0.3 ±0.2	-2.2 ±1.7	8.1 ±1.9
Manure under snow (MUS)	205.3 ±36.6	5.9 ±2.7	<0.1	<0.1	-2.4 ±0.7	3.0 ±1.6
	DRP					
	Snowmelt	Rainfall[b]			Δ WEP	
Control (C)	n/a	0.1 ±0.1			-0.5 ±0.3	
Manure on frozen soil (MF)	n/a	1.0 ±0.7			0.2 ±0.9	
Snow-covered control (SC)	0.1 ±0.1	0.1 ±0.1			-0.5 ±0.3	
Manure on top of snow (MTS)	2.4 ±0.7	1.1 ±0.3			0.7 ±0.4	
Manure between snow (MBS)	1.5 ±0.6	1.2 ±0.3			0.6 ±1.4	
Manure under snow (MUS)	0.7 ±0.2	2.8 ±0.7			0.1 ±0.2	

[a] Values are means ± standard deviation (n/a denotes not applicable).
[b] Rainfall values are sums of surface runoff and subsurface leachate losses.

ment and all of the other treatments. The resulting NH_4-N concentration for the MBS treatment was 5.3 mg kg^{-1} compared to the other treatments, which averaged 3.7 mg kg^{-1}. Alternatively, the NO_3-N concentration increased significantly in both the manured and non-manured treatments (table 4). For the treatments that had both manure and snow, the MBS treatment had a final soil NO_3-N concentration of 11.3 mg kg^{-1}, while the MTS and MUS treatments were not significantly different from the control and averaged 7.7 mg kg^{-1}. Most organic amendments have negligible amounts of NO_3-N, and total N is reported as a combination of NH_4-N and organic N. The decrease in NH_4-N and increase in NO_3-N for all of the treatments suggests that nitrification was still occurring in the soil. Although not directly measured in this study, the relative magnitude of microbial processes among treatments can be inferred from the runoff and leachate losses and the resulting change in soil N levels (table 5). Microorganisms and bacteria play a large role in the fate of nutrients, especially N. Many ecological processes can persist at temperatures near or below freezing even though optimal temperatures may be higher (Campbell et al., 2005). The lack of a difference in final soil NO_3-N concentrations among the MTS, MUS, C, and SC treatments implies that these winter application techniques may not provide any additional N benefit to the subsequent crop compared to non-manured soil. Gupta et al. (2004) and Ryan et al. (2000) observed similar results, in that significant quantities of NO_3-N were found in leachate during the early spring, even when no manure had been applied to the plot. Therefore, application techniques that would decrease the risk of N loss via runoff or leachate and reduce the potential for accelerated eutrophication need to be further researched.

In the current study, the MBS treatment showed the most potential to increase N concentrations in the soil while minimizing contamination of surface-water bodies and groundwater (table 5). The placement of manure between snow may have minimized the effect of several processes that increased susceptibility to nutrient loss. The snow acted as a barrier to N loss via ammonia volatilization prior to and during the beginning stages of the snowmelt. It may have also reduced the effects of the rutting of the snowpack, while still having the benefit of some mulching. These barrier effects resulted in the greatest amount of N left in the soil compared to the other treatments with both manure and snow, which would be available for crop use. Also of significance was the NO_3-N remaining in the soil for the MF treatment (table 5). The lack of snowmelt losses and unfrozen soil during the rainfall simulation allowed more N to infiltrate into the soil profile compared to the treatments with both manure and snow. These results show that manure applied in the winter on frozen soil may benefit the subsequent crop if the first rainfall-runoff event does not occur until after the soil has thawed.

Conclusion

This research was designed as a laboratory-scale study to better understand and identify processes surrounding winter manure application based on its relative placement with respect to snow. The results of this study show that N and P losses in surface runoff and subsurface leachate vary depending on the manure's location with respect to snow. Applying manure prior to a snowfall event increased the concentrations and losses of total N in snowmelt runoff and may decrease infiltration in subsequent rainfall events, resulting in higher concentrations and losses of both N and P in runoff. Applying manure on top of the snow reduced the amount of NH_4-N losses but increased the losses of organic N, DRP, and total P to surface runoff during a snowmelt event. In addition, air quality concerns resulting from increased ammonia volatilization when manure is applied on top of the snow may negate any potential water quality benefits.

An alternative approach to reduce the risk of environmental degradation as well as to provide essential nutrients for the subsequent crop may be to apply manure between layers of snow. Applying manure during the middle of a snow storm, which was done in this study, is not practical for actual farm operations since the weather cannot be controlled. However, equipment could be developed for applying manure into the snowpack. During much of the year, manure is incorporated into the soil through various practices in order to reduce the risk of nutrient loss. A new method to "incorporate" manure into the middle of the snowpack could provide similar benefits. More research needs to be done in order to assess the effects of the depth of the snow above and below the manure and the relative placement of the manure within the snowpack on nutrient loads in surface runoff and subsurface leachate.

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References

Boesch, D. F., R. B. Brinsfield, and R. E. Magnien. 2001. Chesapeake Bay eutrophication: Scientific understanding, ecosystem restoration, and challenges for agriculture. *J. Environ. Qual.* 30(2): 303-320.

Campbell, J. L., M. J. Mitchell, P. M. Groffman, L. M. Christenson, and J. P. Hardy. 2005. Winter in northeastern North America: A critical period for ecological processes. *Frontiers in Ecol. Environ.* 3(6): 314-322.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8(3): 559-568.

Converse, J. C., G. D. Bubenzer, and W. H. Paulson. 1976. Nutrient losses in surface runoff from winter spread manure. *Trans. ASAE* 19(3): 517-519.

Correll, D. L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. *J. Environ. Qual.* 27(2): 261-266.

Culik, M. N., J. W. Doran, and K. A. Richards. 1982. Construction of soil thermocouples for the novice. *SSSA J.* 46(4): 882-884.

Daniel, T. C., A. N. Sharpley, and J. L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. *J. Environ. Qual.* 27(2): 251-257.

Feyereisen, G. W., and G. J. Folmar. 2009. Development of a laboratory-scale lysimeter system to simultaneously study runoff and leaching dynamics. *Trans. ASABE* 52(5): 1585-1591.

Fleming, R., and H. Fraser. 2000. Impacts of winter spreading of manure on water quality: Literature review. Ridgetown, Ontario, Canada: Ridgetown College, University of Guelph.

Gupta, S. C., E. Munyankusi, J. F. Moncrief, F. Zvomuya, and M. Hanewall. 2004. Tillage and manure application effects on mineral nitrogen leaching from seasonally frozen soils. *J. Environ. Qual.* 33(4): 1238-1246.

Hensler, R. F., R. J. Olsen, S. A. Witzel, O. J. Attoe, W. H. Paulson, and R. F. Johannes. 1970. Effect of method of manure handling on crop yields, nutrient recovery, and runoff losses. *Trans. ASAE* 13(6): 726-731.

Klausner, S. D., P. J. Zwerman, and D. F. Ellis. 1976. Nitrogen and phosphorus losses from winter disposal of dairy manure. *J. Environ. Qual.* 5(1): 47-49.

Kongoli, C. E., and W. L. Bland. 2002. Influence of manure application on surface energy and snow cover: Field experiments. *J. Environ. Qual.* 31(4): 1166-1173.

Kværnø, S. H., and L. Øygarden. 2006. The influence of freeze-thaw cycles and soil moisture on aggregate stability of three soils in Norway. *Catena* 67(3): 175-182.

Lauer, D. A., D. R. Bouldin, and S. D. Klausner. 1976. Ammonia volatilization from dairy manure spread on the soil surface. *J. Environ. Qual.* 5(2): 134-141.

Ryan, M. C., R. G. Kachanoski, and R. W. Gillham. 2000. Overwinter soil nitrogen dynamics in seasonally frozen soils. *Canadian J. Soil Sci.* 80(4): 541-550.

SAS. 2002. *SAS User's Guide: Statistics.* Cary, N.C.: SAS Institute, Inc.

Sharpley, A. N., R. W. McDowell, and P. J. A. Kleinman. 2001. Phosphorus loss from land to water: Integrating agricultural and environmental management. *Plant and Soil* 237(2): 287-307.

Sinha, T., K. A. Cherkauer, and V. Mishra. 2010. Impacts of historic climate variability on seasonal soil frost in the Midwestern United States. *J. Hydrometeorol*. 11(2): 229-252.

Srinivasan, M. S., R. B. Bryant, M. P. Callahan, and J. L. Weld. 2006. Manure management and nutrient loss under winter conditions: A literature review. *J. Soil and Water Cons.* 61(4): 200-208.

Steenhuis, T. S., G. D. Bubenzer, J. C. Converse, and M. F. Walter. 1981. Winter-spread manure nitrogen loss. *Trans. ASAE* 24(2): 436-449.

van Vliet, L. J. P., B. J. Zebarth, and G. Derkesn. 2002. Effect of fall-applied manure practices on runoff, sediment, and nutrient surface transport from silage corn in south coastal British Columbia. *Canadian J. Soil Sci.* 82(4): 445-456.

Williams, M. R., G. W. Feyereisen, G. J. Folmar, and H. S. Lin. 2010. Experimental system for simulating a natural soil temperature profile during freeze-thaw cycles. *Applied Eng. in Agric.* 26(5): 843-848.

Young, R. A., and R. F. Holt. 1977. Winter-applied manure: Effects on annual runoff, erosion, and nutrient movement. *J. Soil and Water Cons.* 32(5): 219-222.

Young, R. A., and C. K. Mutchler. 1976. Pollution potential of manure spread on frozen ground. *J. Environ. Qual.* 5(2): 174-178.

Zuzel, J. F., and J. L. Pikul. 1987. Infiltration into a seasonally frozen agricultural soil. *J. Soil and Water Cons.* 42(6): 447-450.