Temperature and Manure Placement in a Snowpack Affect Nutrient Release from Dairy Manure during Snowmelt

Journal:	*Journal of Environmental Quality*
Manuscript ID	JEQ-2017-12-0464-TR.R1
Manuscript Type:	Technical Research Paper
Technical Report Subtypes:	Surface Water Quality
Date Submitted by the Author:	05-Mar-2018
Complete List of Authors:	Vadas, Peter; USDA-ARS-DFRC, Stock, Melanie; University of Wisconsin Feyereisen, Gary; USDA-ARS, Soil and Water Management Research Unit Arriaga, Francisco; University of Wisconsin, Deptartment of Soil Science Good, Laura Karthikeyan, K.G.; University of Wisconsin,
Keywords:	manure, snowmelt, nutrients

Temperature and Manure Placement in a Snowpack Affect Nutrient Release from Dairy Manure during Snowmelt

Peter A. Vadas*, Melanie N. Stock, Gary W. Feyereisen, Francisco J. Arriaga, Laura W. Good,
and K.G. Karthikeyan

P.A. Vadas, USDA-ARS, U.S. Dairy Forage Research Center, 1925 Linden Drive West, Madison, WI 53706. M.N Stock, F.J. Arriaga, L.W. Good, and K.G. Karthikeyan, University of Wisconsin-Madison. G.W. Feyereisen, USDA-ARS, Soil and Water Management Research Unit, St Paul., MN. *Corresponding author: (peter.vadas@ars.usda.gov), 608-890-0069 (phone), 608-890-0076 (fax).

Abstract

Agricultural nutrient management is an issue due to nitrogen (N) and phosphorus (P) losses from fields and water quality degradation. Better information is needed on the risk of nutrient loss in runoff from dairy manure applied in winter. We investigated the effect of temperature on nutrient release from liquid and semi-solid manure to water, and of manure quantity and placement within a snowpack on nutrient release to melting snow. Temperature did not affect manure P and ammonium-N (NH_4) release during water extraction. Manure P release, but not NH_4-N release, was significantly influenced by the water-to-manure solids extraction ratio. During snowmelt, manure P release was not significantly affected by manure placement in the snowpack, and the rate of P release decreased as application rate increased. Water extraction data can reliably estimate P release from manure during snowmelt; however, snowmelt water interaction with manure of greater solids content and subsequent P release appears incomplete compared to liquid manures. Manure NH_4-N released during snowmelt was statistically the same regardless of application rate. For the semi-solid manure, NH_4-N released during snowmelt increased with the depth of snow covering it, most likely due to reduced NH_3 volatilization. For the liquid manure, there was no effect of manure placement within the snowpack on NH_4-N released during snowmelt. Water extraction data can also reliably estimate manure NH_4-N release during snowmelt as long as NH_3 volatilization is accounted for with liquid manures for all placements in a snowpack and semi-solid manures applied on top of snow.

Agricultural nutrient management continues to be an important area of scientific research and policy development due to concerns over N and P losses in surface runoff from farm fields and subsequent water quality degradation (Carpenter et al., 1998; Parris, 2011). Research has consistently shown that surface manure application to fields without incorporation can be a significant source of N and P loss (Daniel et al., 1998; Kleinman and Sharpley, 2003; Vadas et al., 2007). In many northern U.S. states, as well as Canadian provinces and northern European countries, winter application of dairy manure is common because it reduces the need for expensive manure storage, allows time for manure spreading when there are fewer on-field activities, and potentially reduces soil compaction from heavy equipment if soil is frozen (Srinivasan et al., 2006). Because soils are frozen, winter-applied dairy manure is typically surface applied and left unincorporated. This fact, combined with regular and significant runoff from snowmelt and rain-on-snow events, has prompted many states to restrict winter spreading of dairy manure (Srinivasan et al., 2006), including relatively new rules in Iowa (http://www.iowadnr.gov/About-DNR/DNR-News-Releases/ArticleID/1096). However, there has been relatively little research on nutrient loss from winter applied manure as support for restrictions, especially compared to research on manure nutrient loss during non-winter periods (see citations below).

The potential for manure nutrient runoff during winter is complex and can vary due to infiltration, runoff, erosion, and nutrient cycling processes, all of which are sensitive to air temperatures and frozen soil conditions. Nutrient loss may also vary with manure spreading practices, especially relative to manure placement beneath or on top of snow and the effect of manure on rates of snow melt (Kongoli and Bland, 2002). Detailed studies of soil and manure interactions and the hydrological processes that affect nutrient transport under winter conditions are limited. Most studies have been observational with mixed results regarding the degree to which winter manure application increases the risk of nutrient runoff relative to manure application in other seasons. A majority of research was conducted before 1980 (Converse et al., 1976; Steenhuis et al., 1981; Young and Mutchler, 1976; Young and Holt, 1977; Klausner et al., 1976; Phillips et al., 1981). While there has been some more recent research (Hansen et al., 2000; Komiskey et al., 2011; Lewis and Makarewicz, 2009; Owens et al., 2011; Ulen, 2003), it was observational at the field-scale or larger, and did not provide data on liquid manures. The review paper of Srinivasan et al. (2006) details the results of most of these studies. Only the recent research of Williams et al. (2011; 2012b, a) has investigated winter processes at the controlled lab scale. Overall, a process-level understanding of nutrient cycling and transport processes associated with winter manure application is lacking, especially for liquid manures.

Our goal is to improve the understanding and modeling of biochemical and physical processes controlling frozen-soil and snowmelt infiltration, runoff, and nutrient loss from soil and winter-applied dairy manure through a series of lab and field-plot scale experiments. Lab experiments, such as the ones reported here, investigate specific processes under controlled conditions at small scales rather than under variable weather at field scales, which combined can make it difficult to identify relative importance of multiple processes. The specific objectives in the current lab experiments were to 1) investigate if less P and NH_4 are released from manure to water due to low temperatures that would occur during snowmelt (as compared to rain events in non-winter periods); 2) investigate the effect of dairy manure solids content, application amount, and placement within a snowpack on P and NH_4 release to melting snow; and 3) determine if relationships from Objective 1 can reliably predict nutrient release from manure during snowmelt in Objective 2.

Materials and Methods

Manure Extraction Experiments at Different Temperatures

We collected three dairy manures from Holstein lactating cows: i) a liquid manure at the University of Wisconsin cattle research center in Arlington, WI (Arlington liquid); ii) a semi-solid manure at the USDA Dairy Forage Research Center (DFRC semi-solid) farm in Prairie du Sac, WI; and iii) a semi-solid manure from a commercial farm in Minnesota (MN manure). The Arlington liquid manure was from a storage lagoon and had a solids content of 4.6% as determined gravimetrically after drying at 65°C. Manure in the lagoon was from a barn flush system where bedding sand had been separated by gravity settling. On a dry-weight basis, total N content was 77.6 g kg^{-1}, and total P content was 11.0 g kg^{-1}. The DFRC (12.6% solids) and MN (11.6% solids) semi-solid manures were both collected from the floor of free-stall barns at the point of mechanical consolidation. For the DFRC manure, dry-weight-basis total N content was 28.0 g kg^{-1}, and total P content was 5.3 g kg^{-1}. For the MN manure, dry-weight-basis total N content was 43.8 g kg^{-1}, and total P content was 9.0% g kg^{-1}. Manures were stored at 4°C when not in use.

We conducted a series of manure extractions with water at different temperatures to investigate if cold temperatures that occur during snowmelt reduce nutrient release from manure compared to warmer temperatures during non-winter rain events. We conducted all extractions in triplicate. Our procedures followed those of Kleinman et al. (2002) and Vadas and Kleinman (2006) where fresh manure was shaken with deionized water for 1 h at different extraction ratios (cm^3 g^{-1}, dry weight equivalent). Our extraction ratios included 50:1, 100:1, 250:1, and 500:1, and temperatures included 22, 15, 10, and 5°C. The MN manure was also extracted at 1°C. For extractions, we weighed manure and water into separate flasks, placed them into a temperature-controlled shaker and let them equilibrate to the desired temperature for at least 24 h without shaking. We then combined the water and manure, shook the mixtures for 1 h, and filtered them through 0.45μm filters. We analyzed the filtered samples for dissolved reactive P (DRP) colorimetrically (Murphy and Riley, 1962) on a spectrophotometer, and for NH_4–N and NO_3–N on a Lachat automated analyzer (Hach Company, Loveland, CO) using QuickChem Methods 12-107-06-2-A (ammonium) and 12-107-04-1-B (nitrate). Throughout the experiments, NO_3–N concentrations in manure extractions and snowmelt leachings (see below) were negligible, so we do not present data for this N form.

Snowmelt Leaching Experiments

We designed these experiments to investigate nutrient release from manure to melting snow water. This is the first step in understanding and modeling potential manure nutrient transport in runoff. We therefore conducted experiments with snow and manure only, in the absence of underlying soil. We used only the Arlington liquid manure and DFRC semi-solid manure for these leaching experiments. We conducted experiments in triplicate using 15-cm diameter funnels that had flat bottoms and a series of small drainage holes. We collected natural snow and stored it frozen until use. We added snow and manure to funnels to achieve three rates of manure, and three manure placements in a snowpack, which were below snow, between two equivalent snow layers, and on top of snow. For the liquid manure, we added a snow equivalent of 1400 mL of water and manure at three wet-weight amounts of 98, 197 and 394 g. This achieved a relatively wide range of liquid (including snow and manure liquid) to manure dry matter ratios of 96, 174, and 331 $cm^3\ g^{-1}$ (Table 4). For the semi-solid manure, we added a snow equivalent of 1250 mL of water and manure at wet-weight rates of 32, 68 and 136 g. This achieved liquid to manure dry matter ratios of 74, 144, and 315 $cm^3 g^{-1}$ (Table 4). For each funnel, we froze a piece of acid-washed, nylon screen in 30 mL of deionized water and placed the screen in the funnel before adding any manure or snow. This prevented any immediate loss of manure through funnels before snowmelt began. When assembled, we placed all funnels in a cold room at approximately 4°C and allowed snow to melt, which took between 44 to 58 h. During melt, we collected all leachate in increments of 250-300 mL. We filtered and analyzed all samples for NH_4 and P as described above.

Statistical Analysis

We used the general linear model of SAS (SAS Version 9.4) along with Tukey's mean separation to conducted a statistical analysis of results. For the water extraction experiment, variables of DRP and NH_4-N, total treatment sums of squares (SS) for the fixed effects in the ANOVA were partitioned into partial SS associated with the three manure types, four extraction ratios, five temperatures, and all their two-way and three-way treatment interactions. We used partial SS to determine the percentage of total DRP and NH_4-N associated with each treatment effect or treatment interaction. Treatment differences discussed in the text were significant at the 0.05 probability level. We conducted a similar statistical analysis for the funnel leaching experiments, where fixed effects were the two manure types, three application rates, three placements in the snowpack, and all their two-way and three-way treatment interactions.

Results and Discussion

Manure Extraction Experiments

Throughout the discussion, we refer to DRP analyzed in manure extractions as water extractable P (WEP) to be consistent with terminology in previous studies on manure P extractability (Kleinman et al., 2002; Vadas and Kleinman, 2006; Kleinman et al., 2005). Figure 1 shows results for manure WEP (mg kg^{-1} dry weight equivalent) for the three dairy manures as a function of extraction ratio and temperature. Statistical analysis indicated that only extraction ratio had a significant effect on WEP, and explained 60% of its variability (Table 1). This was true for WEP expressed on a mass basis (mg kg^{-1} dry weight equivalent) or as a percent of total P in the manure. Manure type and the manure by extraction ratio interaction each explained 16% of WEP variability, but were not statistically significant. Across all three manures, temperature did not significantly affect WEP, even though there was less WEP from the Arlington liquid manure as temperature decreased from 22^{o}C to 10^{o}C, with no further decrease less than 10^{o}C. This suggests cold temperatures do not affect P release from manure substantially enough that models need to account for the variable (Bechmann et al., 2005).

Figure 2 shows results for water extractable manure NH_4-N as a function of extraction ratio and temperature. Statistical analysis showed that only manure type had a significant effect on extractable NH_4-N, and explained 98% of the data variability (Table 1). There was greater extractable NH_4-N for the liquid manure than the semi-solid manures, which did not differ from each other. While this statistical effect of manure type was true on a mass basis (mg kg^{-1} dry weight equivalent), it was not true for NH_4-N expressed as a percent of total N in manure. Since total N content varied from 28.0 to 77.6 g kg^{-1} across manures, comparing data as a percent of total N may be more equitable. Given that, Figure 2 shows that manure NH_4-N release to water was fairly rapid and complete regardless of temperature, extraction ratio, or manure type. Good (2002) also observed no effect of extraction ratio on manure NH_4-N release. This suggests that models do not need to account for these variables when estimating NH_4-N release from manure during snowmelt.

Phosphorus Dynamics during Snowmelt Leaching

In all experiments, DRP concentrations in snowmelt water in the absence of manure were less than 0.05 mg L^{-1}. Results in Figures 3 and 4 show that DRP concentrations in incremental leachate for both the liquid manure and the DFRC semi-solid manure increased as snowmelt progressed. These data are consistent with our lab extraction data that DRP release is a function of how much water interacts with manure. Thus during snowmelt when liquid water interaction with manure is gradual, DRP release is more likely to increase as snowmelt proceeds and leads to interaction with more water (Kleinman et al., 2002).

Table 3 presents cumulative manure DRP released (mg) for both the liquid and semi-solid manures over the entire snowmelt period. Statistical analysis in Table 2 shows that on a mass basis (mg) there was no effect of manure type, placement in the snowpack, or application rate on cumulative DRP released. However, when expressed as a percent of total manure P applied, there was an effect of application rate on cumulative DRP released (Table 2). Thus, the proportion of applied manure total P that leached decreased as application rate increased. The three manure application rates during snowmelt represented about 50, 100, and 200 mg applied total P for the liquid manure and 21, 45, and 91 mg for the DFRC semi-solid manure for the high, medium, and low application rates, respectively (Table 4). Therefore, the amount of manure DRP leached during snowmelt was about 5, 9, and 17% of total P applied for the high, medium, and low application rates for both manures. These results are consistent with our lab extraction data showing that P leaching is a function of the water:solids extraction ratio and that a greater percentage of manure P is released at greater ratios (Vadas et al., 2004; Vadas et al., 2005). In the snowmelt leaching experiments, as the amount of applied manure increased, the ratio of snow water to manure solids (equivalent to extraction ratio during the water extraction experiments) decreased, and thus the percentage of applied P that was released also decreased.

There was no significant effect of manure placement within the snowpack on cumulative DRP released (Tables 2 and 3). Young and Mutchler (1976) suggested that manure applied below snow may have greater potential to interact with liquid snowmelt water and lose more nutrients in runoff. However, in controlled laboratory experiments using soil boxes, Williams et al. (2011) found less P loss in runoff from manure applied below snow compared to on top of or within snow and suggested this was because manure remained frozen below snow (due to influence of frozen soil) and was less susceptible to P loss. Phosphorus loss in runoff was the same for manure applied on top of or within snow. Our experiments did not have underlying soil and are not strictly comparable to these runoff studies. However, our data are consistent with those of Williams et al. (2011) for manure applied on top of or within snow, and suggest that snowmelt water interaction with manure and release of P, and thus potential P loss in snowmelt runoff, is functionally similar regardless of where manure is in the snowpack. Instead, site snowmelt dynamics, degree of snowmelt water interaction with manure, and runoff hydrology are likely more dominant mechanisms controlling manure P release during snowmelt and potential loss in runoff than manure placement in the snowpack (Kongoli and Bland, 2002). This suggests nutrient runoff models do not need to account for manure placement in a snowpack for P.

Vadas et al. (2004; 2005) showed that manure water extraction data such as those in Figure 1 can be used to reliably estimate how much DRP is leached from manure during a rain event. The equation used in that research to estimate DRP leached from manure by rain was:

$$\text{DRP release} = [1.2W/(W + 73.1)](\text{manure WEP}) \quad [1]$$

where W is the water to manure extraction ratio ($cm^3\ g^{-1}$), WEP is the manure DRP that is extracted (in mass units such as mg or mg kg^{-1}) at a W of 250:1 over 1 h, and DRP release is in the same units as WEP. Equation [1] fit well to the lab extraction data for the DFRC semi-solid manure in Figure 1 ($r^2 = 0.70$), so we applied Eq. [1] to see if it could reliably estimate DRP release from manure during our snowmelt leaching experiments. For the semi-solid manure, manure solids application rates and W values during snowmelt leaching are in Table 4. We estimated a manure WEP of 1560 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1. Applying Eq. [1] resulted in estimated DRP release amounts of 16.1, 10.6, and 6.1 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding measured rates as averaged across manure placements in snow were 4.7, 4.5, and 3.7 mg for high, medium, and low application rates (Table 3).

Clearly, less DRP was leached from the semi-solid manure during snowmelt than Eq. [1] would estimate. If we assume that the basic leaching processes represented by Eq. [1] still applied, underestimated DRP leaching suggests that not all the snowmelt water interacted with manure and that W as applied in Eq. [1] should have been less. In fact, the degree to which measured DRP release was less than that estimated by Eq. [1] was consistent. We calculated that if only 20% of snowmelt water actually interacted with manure, then Eq. [1] W values would be

15, 29, and 63 cm^3 g^{-1}; and corresponding estimated DRP release would be 4.7, 4.5, and 3.5 mg, for the high, medium, and low application rates, respectively. These estimated DRP release values are similar to measured values (Table 3).

Overall, our snowmelt leaching and water extraction data results suggest that for semi-solid manures Eq. [1] can be used in models to estimate DRP release from manure during snowmelt, and that DRP release is not a function of temperature or manure placement in a snowpack during snowmelt. However, the amount of snowmelt water that actually interacts with the manure and subsequent DRP release is significantly less compared to water interaction with manure during a rain event. During modeling research using Eq. [1] to simulate P loss in runoff from winter applied manure, Vadas et al. (2017) found that field scale runoff data also indicated incomplete interaction of snowmelt water with solid beef manure. Clearly, this possibility of incomplete snowmelt water interaction with solid manure and reduced DRP release deserves further investigation, especially as we could find no literature on this topic.

For the Arlington liquid manure, Eq. [1] did not effectively describe the lab WEP extraction data in Figure 1 ($r^2 = 0.05$). The reason for this is unknown, but could be related to manure P mineralogy, which can be a function of animal diet or bedding material (Pagliari, 2011). The liquid manure WEP extraction data instead exhibited a linear increase in manure WEP with W, while Eq. [1] is nonlinear. Therefore, we used data from Figure 1 (as averaged across all temperatures) to represent DRP release from the liquid manure as:

$$\text{DRP release} = (0.005\ W - 0.253)(\text{manure WEP}) \qquad r^2=0.96 \qquad [2]$$

For the liquid manure, manure solids application amounts and W values are in Table 4. We estimated a manure WEP of 1840 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1. Applying Eq. [2] resulted in manure DRP release amounts of 8.4, 10.3 and 7.7 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding measured rates were 7.8, 8.0, and 8.6 mg for the high, medium, and low application rates (Table 3). Similar to the DFRC semi-solid manure, these liquid manure results suggest that lab water extraction data can be used to estimate DRP release from manure during snowmelt, without considering temperature or manure placement in a snowpack during snowmelt. Data also demonstrate that when estimating DRP release from a liquid manure during snowmelt, incomplete snowmelt water interaction with manure does not need to be considered. This may be because liquid manure is more evenly distributed and absorbed into the snowpack than a semi-solid manure, and thus has a potential for greater snowmelt interaction. As before, this possibility of more complete snowmelt interaction with liquid manure but incomplete snowmelt water interaction with more solid manure deserves further investigation.

Nitrogen Dynamics during Snowmelt Leaching

In all leaching experiments, NH_4-N concentrations in snow water without manure were less than 0.30 mg L^{-1}. Results in Figures 3 and 4 show that NH_4-N concentrations in incremental leachate water from both the liquid and semi-solid manures decreased as snowmelt progressed. These data are consistent with our lab extractions that showed NH_4-N release is not a function of how much water interacts with manure. Thus during snowmelt, NH_4-N release would be expected to be rapid even with only low amounts of snowmelt water (first flush phenomenon).

Statistical analysis in Table 2 shows that only manure type had a significant effect on mass (mg) of cumulative NH_4-N leached during snowmelt (Table 3). However, when NH_4-N release was expressed as a function of total N applied in manure, no treatment variables had a significant effect on NH_4-N leached (Table 2). Thus, a similar percentage of applied total N leached from manure regardless of application rate and thus snow water:manure solids ratio. For both manures, an average of 19.2% (s.d. of 2.3%) of applied manure total N was leached.

For the semi-solid manure, although placement in the snowpack was not a significant factor (Table 2), the amount of NH_4-N leached during snowmelt consistently increased with the depth of snow covering it (Table 3). This is most likely because manure applied on top of snow, and even between snow layers, had longer direct exposure to the air above it, had greater NH_3 volatilization, and thus had less NH_4-N available for leaching loss (Williams et al., 2011; Lauer et al., 1976). Steenhuis et al. (1979) observed about 35% greater NH_3 volatilization from a dairy manure (16% solids) placed on top of a snow pack compared to below a 10cm snowpack over four days. Similarly, we observed about 30% more NH_4-N in leachate from our semi-solid manure when manure was below the snowpack compared to on top. An average of 20.6% (s.d. of 1.7%), 18.6% (s.d. of 1.5%), and 13.5% (s.d. of 0.7%) of applied manure total N was leached as NH_4-N for the manure below, in between, and on top of snow, respectively. For the liquid manure at a given manure application rate, there was no trend of manure placement within the snowpack on NH_4-N leached during snowmelt (Table 3). An average of 20.9% (s.d. of 2.3%) of manure total N was leached as NH_4-N. Therefore, our data suggest that NH_3 volatilization may not vary as a function of placement in a snowpack for liquid manure.

Similar to P, we investigated if our water extraction data could reliably estimate NH_4-N release from manure during snowmelt. Combining the data from all three manures in Figure 2, we developed the equation below (similar to Eqs. [1] and [2]):

$$NH_4 \text{ release} = (0.0004\ W - 0.758)(\text{manure } NH_4\text{-N}) \qquad r^2=0.50 \qquad [3]$$

Solids application rates and W values during snowmelt leaching are in Table 4. We estimated manure NH_4-N from maximum amounts extracted during water extractions (Figure 2). Applying Eq. [3] for the semi-solid manure resulted in predicted NH_4-N release of 86.3, 44.7, and 22.8 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding average measured NH_4-N release rates when manure was applied below or between snow layers were 88.6, 45.7, and 24.0 mg (Table 3). Therefore, Eq. [3] reliably estimated manure NH_4-N release for these two manure placements. However, corresponding measured NH_4-N release rates when manure was applied on top of snow was 64.3, 30.7, and 15.9 mg (Table 3). Therefore, Eq. [3] over-estimated manure NH_4-N release for this manure placement. It is reasonable to assume that overprediction is due to unaccounted for NH_3 volatilization from manure applied on top of snow. In fact, if we assume a NH_3 volatilization rate of 35% for manure applied on top of snow, as reported by Steenhuis et al. (1979) (i.e., 35% less manure NH_4-N available to leach), predicted NH_4-N release in snowmelt would be 56.1, 29.0, and 14.8 mg, which is close to measured values. Converse to P, these data also demonstrate that when estimating manure NH_4-N release from a semi-solid manure during snowmelt, incomplete snowmelt water interaction with manure does not need to be considered. This may be because NH_4-N release is much less sensitive to the amount of water that interacts with manure (Fig. 2).

For the liquid manure, manure solids application rates and W values are in Table 4. Applying Eq. [3] resulted in predicted NH_4-N release amounts of 479.0, 239.5, and 112.7 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding measured NH_4-N release rates were clearly much less at 266.7, 150.1, and 79.5 mg (Table 3). If we attribute overprediction to NH_3 volatilization from applied manure, a volatilization rate of 35% of applied manure NH_4-N would result in predicted NH_4-N release during snowmelt of 282.2, 146.6, and 78.9 mg, which agreed well with measured rates. Overall, our data suggest that water extraction data can be used to reliably estimate manure NH_4-N release during snowmelt without having to consider temperature or NH_3 volatilization if a semi-solid to solid manure is covered by snow. However, NH_3 volatilization needs to be accounted for with liquid manures at all placements in a snowpack and a semi-solid manure applied on top of snow.

Conclusions

Our lab-scale experiments suggest that temperature may not significantly influence manure WEP and NH_4-N release to water. Also, manure WEP release, but not NH_4-N release, to water will be influenced by the water-to-manure solids ratio. Manure placement within a snowpack may not significantly influence snowmelt interaction with manure and leaching of DRP. For semi-solid manures, the amount of NH_4-N leached during snowmelt can increase with the depth of snow covering it. This is mostly likely because manure applied on top of snow, and even between snow layers, has greater NH_3 volatilization and thus less NH_4-N available for leaching loss. For liquid manures, NH_3 volatilization may not vary as a function of placement in a snowpack, but liquid manures applied to snow will have greater NH_3 volatilization than more solid manures unless the solid manures are applied on top of snow and have significant NH_3

volatilization. Finally, lab water extractions can be used to reliably estimate manure NH_4-N release during snowmelt, but variations in NH_3 volatilization need to be accounted for with liquid manures at all placements in a snowpack and a semi-solid manure applied on top of snow. Lab water extractions can also be used to estimate DRP release from manure during snowmelt; but for semi-solid to solid manures, the amount of snowmelt water that actually interacts with the manure and subsequent WEP release is significantly less compared to water interaction with manure during a rain event. The same is not true for liquid manures applied to snow. This may be because liquid manure is more evenly distributed and absorbed into a snowpack than a semi-solid manure, and thus has a greater potential for complete snowmelt interaction. This possibility of more complete snowmelt interaction with liquid manures but incomplete snowmelt water interaction with more solid manure during DRP release deserves further investigation, especially as a function of a range of manure solids content. Overall, our data will help improve simulation models that can be applied to explore the management and environmental implications of winter manure spreading and variable winter runoff conditions.

References

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley, and L.S. Saporito. 2005. Freeze-thaw effects on phosphorus loss in runoff froin manured and catch-cropped soils. J. Environ. Qual. 34:2301-2309.

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. Ecol. Appl. 8:559-568.

Converse, J.C., G.D. Bubenzer, and W.H. Paulson. 1976. Nutrient Losses in Surface Runoff from Winter Spread Manure. Trans. ASAE 19:517-519.

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

Good, L.W. 2002. Mechanisms controlling phosphorus loss to water from animal manures and manure-amended soils. Ph.D. diss., Univ. Wisconsin, Madison.

Hansen, N.C., S.C. Gupta, and J.F. Moncrief. 2000. Snowmelt runoff, sediment, and phosphorus losses under three different tillage systems. Soil Till Res 57:93-100.

Klausner, S.D., P.J. Zwerman, and D.F. Ellis. 1976. Nitrogen and Phosphorus Losses from Winter Disposal of Dairy Manure. J. Environ. Qual. 5:47-49.

Kleinman, P.J.A., and A.N. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J. Environ. Qual. 32:1072-1081.

Kleinman, P.J.A., A.N. Sharpley, A.M. Wolf, D.B. Beegle, and P.A. Moore. 2002. Measuring water-extractable phosphorus in manure as an indicator of phosphorus in runoff. Soil Sci. Soc. Am. J. 66:2009-2015.

Kleinman, P.J.A., A.M. Wolf, A.N. Sharpley, D.B. Beegle, and L.S. Saporito. 2005. Survey of water-extractable phosphorus in livestock manures. Soil Sci. Soc. Am. J. 69:701-708.

Komiskey, M.J., T.D. Stuntebeck, D.R. Frame, and F.W. Madison. 2011. Nutrients and sediment in frozen-ground runoff from no-till fields receiving liquid-dairy and solid-beef manures. J. Soil Water Conserv. 66:303-312.

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

Lauer, D.A., D.R. Bouldin, and S.D. Klausner. 1976. Ammonia Volatilization from Dairy Manure Spread on Soil Surface. J. Environ. Qual. 5:134-141.

Lewis, T.W., and J.C. Makarewicz. 2009. Winter application of manure on an agricultural watershed and its impact on downstream nutrient fluxes. J Great Lakes Res 35:43-49.

Murphy, J., and J.P. Riley. 1962. A Modified Single Solution Method for Determination of Phosphate in Natural Waters. Anal. Chim. Acta 27:31-36.

Owens, L.B., J.V. Bonta, M.J. Shipitalo, and S. Rogers. 2011. Effects of Winter Manure Application in Ohio on the Quality of Surface Runoff. J. Environ. Qual. 40:153-165.

Pagliari, P.H. 2011. Investigation of inorganic and organic phosphorus in animal manure and their effects on soil test phosphorus. Ph.D. diss., Univ. Wisconsin, Madison.

Parris, K. 2011. Impact of Agriculture on Water Pollution in OECD Countries: Recent Trends and Future Prospects. Int J Water Resour D 27:33-52.

Phillips, P.A., J.L.B. Culley, F.R. Hore, and N.K. Patni. 1981. Pollution Potential and Corn Yields from Selected Rates and Timing of Liquid Manure Applications. Trans. ASAE 24:139-144.

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 Water Conserv. 61:200-209.

Steenhuis, T.S., G.D. Bubenzer, and J.C. Converse. 1979. Ammonia Volatilization of Winter Spread Manure. Trans. ASAE 22:152-&.

Steenhuis, T.S., G.D. Bubenzer, J.C. Converse, and M.F. Walter. 1981. Winter-Spread Manure Nitrogen Loss. Trans. ASAE 24:436-442.

Ulen, B. 2003. Concentrations and transport of different forms of phosphorus during snowmelt runoff from an illite clay soil. Hydrological Processes 17:747-758.

Vadas, P.A., L.W. Good, W.E. Jokela, K.G. Karthikeyan, F.J. Arriaga, and M. Stock. 2017. Quantifying the impact of seasonal and short-term manure application decisions on phosphorus loss in surface runoff. J. Envrion. Qual. 46:doi:10.2134/jeq2016.2106.0220.

Vadas, P.A., B.E. Haggard, and W.J. Gburek. 2005. Predicting dissolved phosphorus in runoff from manured field plots. J. Environ. Qual. 34:1347-1353.

Vadas, P.A., R.D. Harmel, and P.J.A. Kleinman. 2007. Transformations of soil and manure phosphorus after surface application of manure to field plots. Nutr. Cycl. Agroeco. 77:83-99.

Vadas, P.A., and P.J.A. Kleinman. 2006. Effect of methodology in estimating and interpreting water-extractable phosohorus in animal manures. J. Environ. Qual. 35:1151-1159.

Vadas, P.A., P.J.A. Kleinman, and A.N. Sharpley. 2004. A simple method to predict dissolved phosphorus in runoff from surface-applied manures. J. Environ. Qual. 33:749-756.

Williams, M.R., G.W. Feyereisen, D.B. Beegle, and R.D. Shannon. 2012a. Soil Temperature Regulates Nitrogen Loss from Lysimeters Following Fall and Winter Manure Application. Trans. ASABE 55:861-870.

Williams, M.R., G.W. Feyereisen, D.B. Beegle, and R.D. Shannon. 2012b. Soil Temperature Regulates Phosphorus Loss from Lysimeters Following Fall and Winter Manure Application. Trans. ASABE 55:871-880.

Williams, M.R., G.W. Feyereisen, D.B. Beegle, R.D. Shannon, G.J. Folmar, and R.B. Bryant. 2011. Manure Application under Winter Conditions: Nutrient Runoff and Leaching Losses. Trans. ASABE 54:891-899.

Young, R.A., and R.F. Holt. 1977. Winter-Applied Manure - Effects on Annual Runoff, Erosion, and Nutrient Movement. J. Soil Water Conserv. 32:219-222.

Young, R.A., and C.K. Mutchler. 1976. Pollution Potential of Manure Spread on Frozen Ground. J. Environ. Qual. 5:174-179.

Figure Captions

Figure 1. Manure WEP release for the Arlington liquid dairy manure and the DFRC and MN semi-solid dairy manures during water extraction experiments as a function of extraction temperature and extraction ratio (water to manure solids, $cm^3 g^{-1}$). Bars indicate the standard deviation of the means.

Figure 2. Manure NH_4-N release for the Arlington liquid dairy manure and the DFRC and MN semi-solid dairy manures during water extraction experiments as a function of extraction temperature and extraction ratio (water to manure solids, $cm^3 g^{-1}$). Bars indicate the standard deviation of the means.

Figure 3. Change in dissolved P and NH_4-N concentrations in snowmelt water with increasing leachate volume during snowmelt leaching experiments with the Arlington liquid dairy manure applied at three different rates. Data for a given rate are averaged across manure placements in the snowpack. Bars indicate the standard deviation of the means.

Figure 4. Change in dissolved P and NH_4-N concentrations in snowmelt water with increasing leachate volume during snowmelt leaching experiments with the DFRC semi-solid dairy manure applied at three different rates. Data for a given rate are averaged across manure placements in the snowpack. Bars indicate the standard deviation of the means.

Table 1. ANOVA for effects of manure, extraction ratio, and temperature on manure WEP and NH_4-N extracted during water extraction experiments. Data are presented for concentrations (mg kg^{-1}) as well percent of total P or total N in manure.

Source of Treatment Variation		WEP		Percent of Total P		NH_4-N		Percent of Total N	
	Df	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt
Manure	2	0.1471	16.4	0.1917	17.3	0.0017	97.7	0.1376	90.9
Ratio	3	0.0044	58.2	0.0077	62.8	0.9792	1.2	0.9645	5.9
Temperature	4	0.9553	2.8	0.9821	2.0	1.0000	0.1	1.0000	0.2
Manure * Ratio	6	0.6822	16.0	0.8775	11.5	1.0000	0.4	1.0000	0.8
Manure * Temperature	6	0.9952	2.7	0.9964	2.9	1.0000	0.3	1.0000	1.2
Ratio * Temperature	12	1.0000	0.9	1.0000	0.7	1.0000	0.1	1.0000	0.5
Manure * Ratio * Temperature	18	1.0000	2.9	1.0000	2.9	1.0000	0.1	1.0000	0.6

Table 2. ANOVA for effects of manure, extraction ratio, and temperature on manure DRP and NH$_4$-N leached during snowmelt leaching experiments. Data are presented for mass (mg) as well percent of total P or total N applied to funnels as manure.

Source of Treatment Variation		DRP		Percent of Total P		NH$_4$-N		Percent of Total N	
	Df	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt
Manure	1	0.1006	76.7	0.6992	1.8	0.0254	53.0	0.5713	31.1
Placement	2	0.9632	1.9	0.9981	0.0	0.9857	0.3	0.8993	19.9
Rate	2	0.9928	0.4	0.0423	87.0	0.1710	34.8	0.9286	13.9
Manure * Placement	2	0.8219	10.2	0.7860	5.6	0.9903	0.2	0.9166	16.4
Manure * Rate	2	0.9473	2.8	0.9804	0.5	0.5693	10.4	0.9896	2.0
Placement * Rate	4	0.9991	2.1	0.9999	0.3	0.9993	0.6	0.9992	7.4
Manure * Placement * Rate	4	0.9931	6.0	0.9787	4.9	0.9989	0.8	0.9986	9.4

Table 3. Cumulative manure DRP and NH_4-N release (mg) for the Arlington Liquid and DFRC semi-solid dairy manures during snowmelt experiments as a function of manure application rate (Low, Medium, High) and manure placement within a snowpack (under snow, between snow layers, and on top of snow). Values in parentheses are DRP and NH_4-N release expressed as percentages of total P and total N applied as manure.

Rate	Under	Between	Top	Under	Between	Top
		DRP			NH_4-N	
	mg	mg	mg	mg	mg	mg
			Liquid Manure			
Low	6.5 (13.0)	9.0 (18.0)	10.2 (20.4)	74.2 (21.1)	89.6 (25.5)	74.8 (21.3)
Medium	6.6 (6.6)	9.0 (9.0)	8.4 (8.4)	145.6 (20.7	164.5 (23.4)	140.1 (19.9)
High	7.0 (3.5)	9.2 (4.6)	7.1 (3.6)	279.8 (19.9)	260.7 (18.5)	259.6 (18.9)
			Semi-solid Manure			
Low	4.7 (22.4)	3.4 (16.2)	2.8 (13.3)	25.1 (22.4)	22.8 (20.4)	15.9 (14.2)
Medium	5.4 (12.0)	3.8 (8.4)	4.3 (9.6)	49.7 (20.8)	41.8 (17.5)	30.7 (12.8)
High	5.2 (5.7)	4.3 (4.7)	4.6 (5.1)	90.5 (18.9)	86.7 (18.1)	64.3 (13.4)

Table 4. Data for manure solids applied, water:solids ratio, manure total P and N applied, and predicted DRP and NH_4-N release for both the liquid and semi-solid manures during the snowmelt leaching experiments.

Rate	Manure Solids Applied[1]	Water:Solids Ratio (W)[2]	Manure Total P Applied	Manure Total N Applied	Predicted DRP Release[3]	Predicted NH_4-N Release[4]
	g	cm^3 g^{-1}	mg	mg	mg	mg
			Liquid Manure			
Low	4.5	331.2	49.9	352.3	8.4	78.9
Medium	9.1	174.0	99.9	704.7	10.3	146.6
High	18.2	96.4	199.8	1409.4	7.7	282.2
			Semi-solid Manure			
Low	4.0	316.0	21.3	112.7	6.1	22.8
Medium	8.6	144.0	45.3	239.5	10.6	44.7
High	17.1	74.0	90.7	479.0	16.1	86.3

[1] Dry weight equivalent

[2] Includes water in manure and 1250 mL snow water for semi-solid manure and 1400 mL for liquid manure

[3] Predictions use Eq. [1] for semi-solid manure and Eq. [2] for liquid manure

[4] Predictions use Eq. [3]

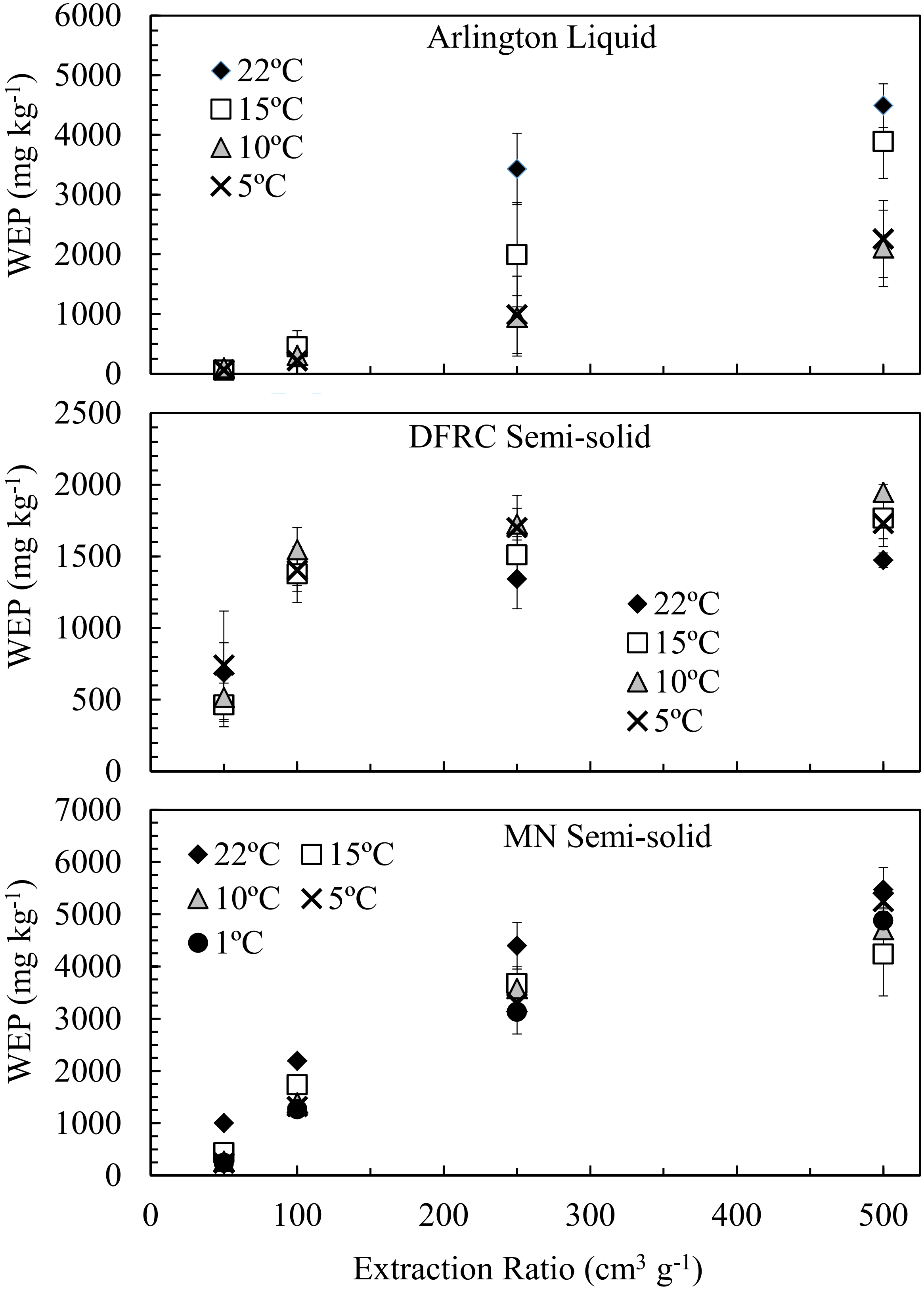

Arlington Liquid
22ºC
15ºC
10ºC
5ºC
WEP (mg kg-1)
6000
5000
4000
3000
2000
1000
0
DFRC Semi-solid
22ºC
15ºC
10ºC
5ºC
WEP (mg kg-1)
2500
2000
1500
1000
500
0
MN Semi-solid
22ºC
15ºC
10ºC
5ºC
1ºC
WEP (mg kg-1)
7000
6000
5000
4000
3000
2000
1000
0
0
100
200
300
400
500
Extraction Ratio (cm3 g-1)

Figure 2.

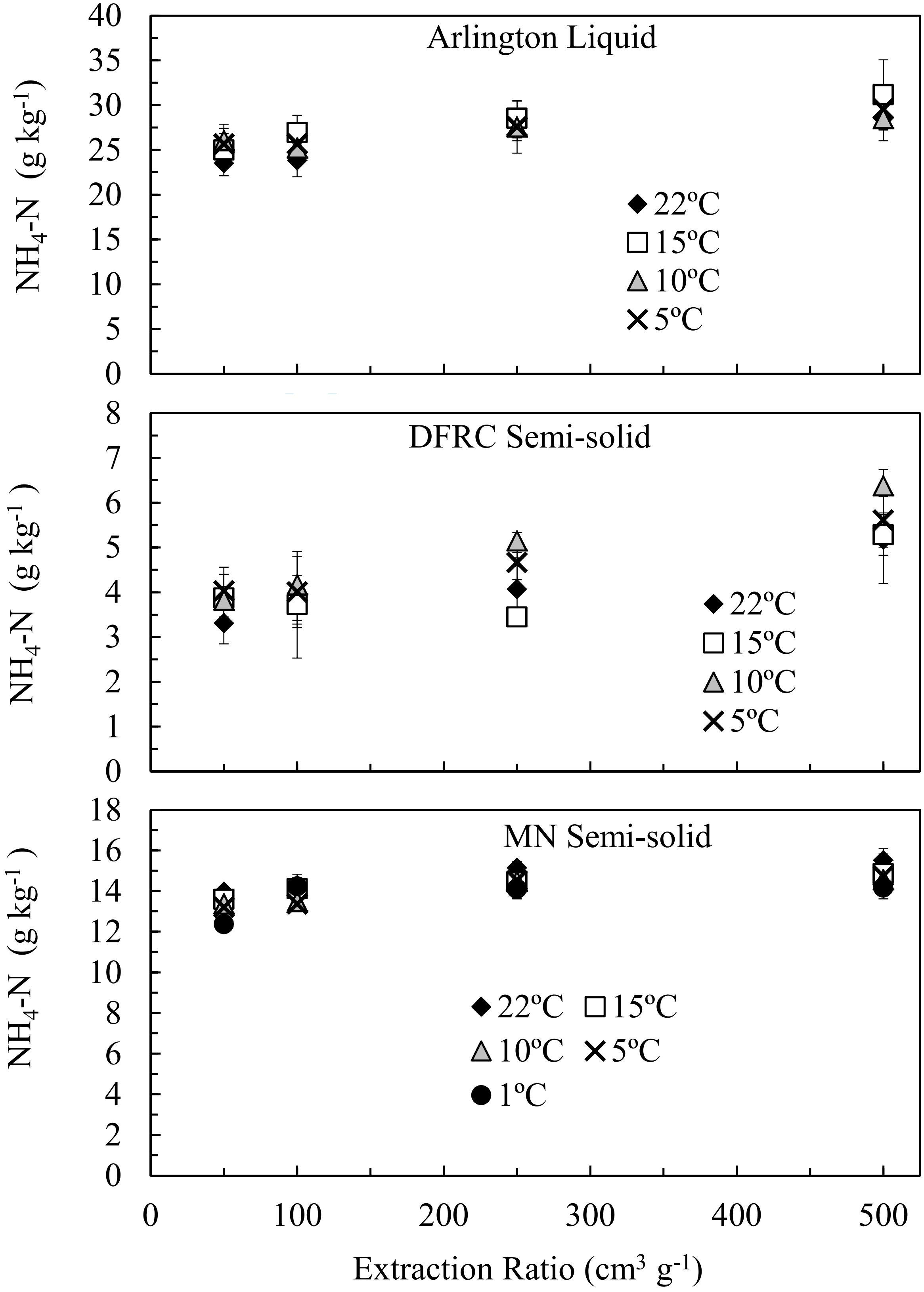

Arlington Liquid
DFRC Semi-solid
MN Semi-solid
NH$_4$-N (g kg^{-1})
◆ 22ºC
□ 15ºC
△ 10ºC
✕ 5ºC
● 1ºC
0
5
10
15
20
25
30
35
40
0
1
2
3
4
5
6
7
8
0
2
4
6
8
10
12
14
16
18
0
100
200
300
400
500
Extraction Ratio (cm^3 g^{-1})

Figure 3

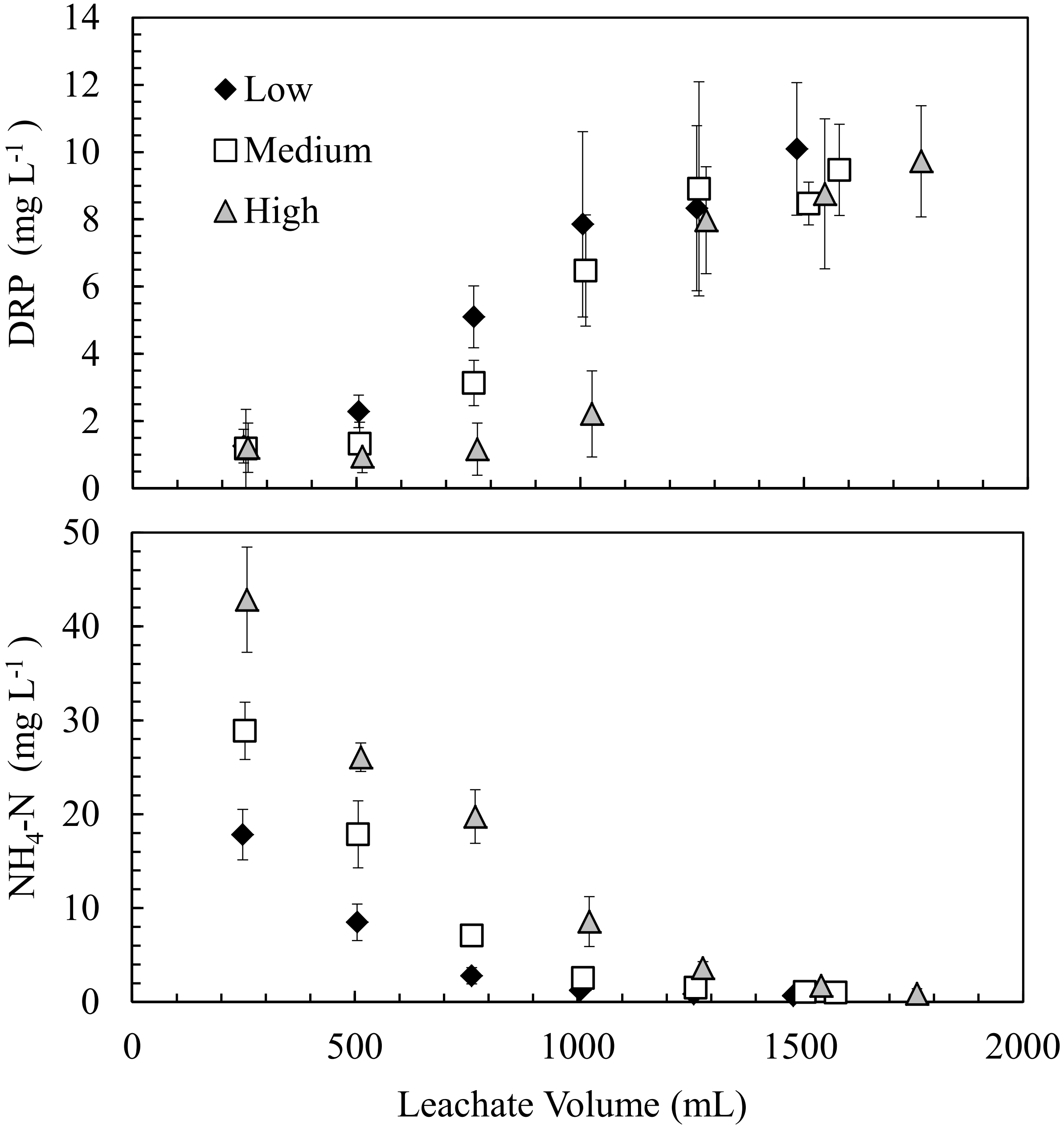
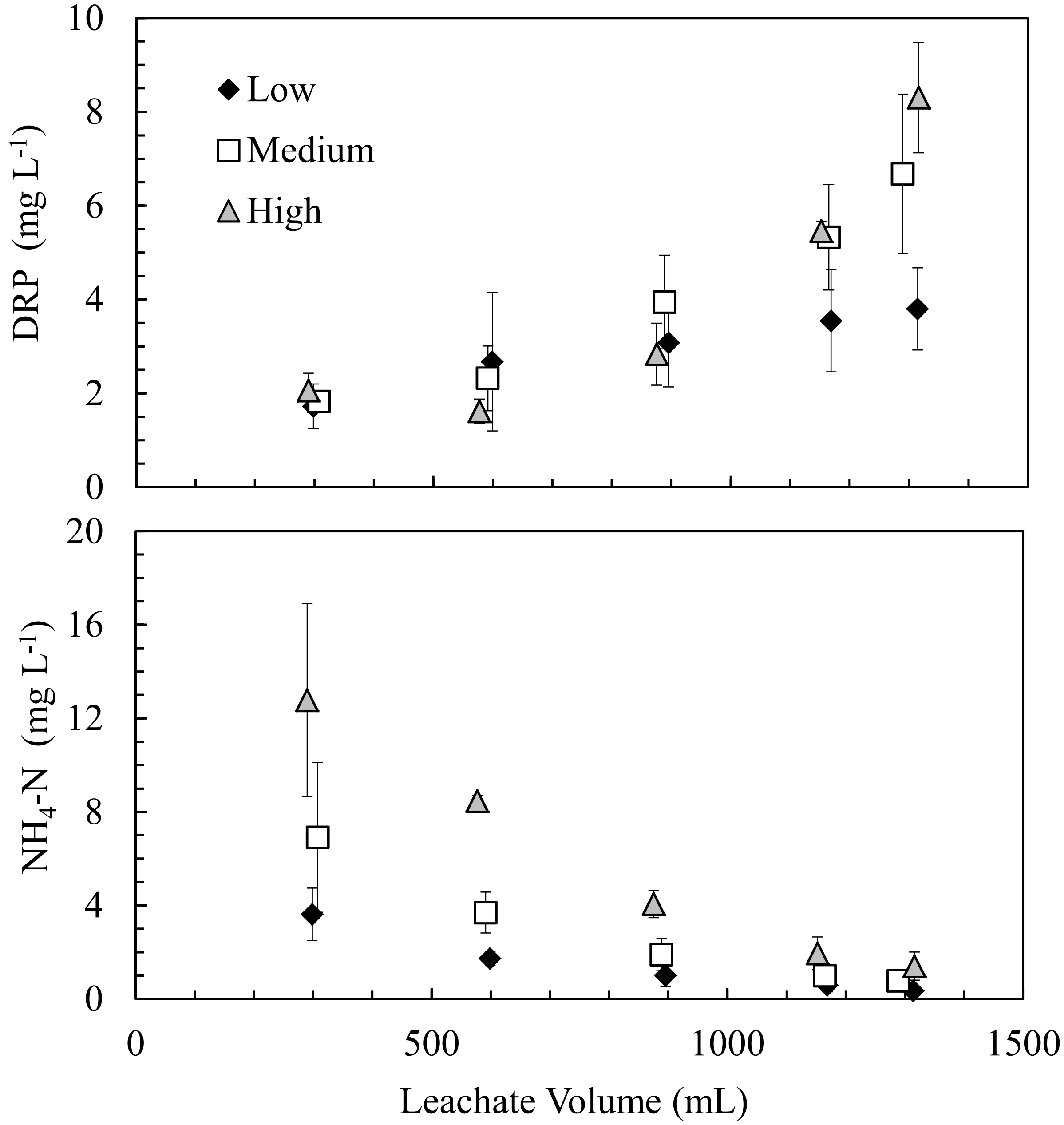

14
12
10
8
6
4
2
0
DRP (mg L^{-1})
◆ Low
□ Medium
△ High
50
40
30
20
10
0
NH$_4$-N (mg L^{-1})
0
500
1000
1500
2000
Leachate Volume (mL)

Figure 4


10
8
6
4
2
0
DRP (mg L^{-1})
◆ Low
□ Medium
△ High
20
16
12
8
4
0
NH$_4$-N (mg L^{-1})
0
500
1000
1500
Leachate Volume (mL)

Temperature and Manure Placement in a Snowpack Affect Nutrient Release from Dairy Manure during Snowmelt

Peter A. Vadas*, Melanie N. Stock, Gary W. Feyereisen, Francisco J. Arriaga, Laura W. Good, and K.G. Karthikeyan

P.A. Vadas, USDA-ARS, U.S. Dairy Forage Research Center, 1925 Linden Drive West, Madison, WI 53706. M.N Stock, F.J. Arriaga, L.W. Good, and K.G. Karthikeyan, University of Wisconsin-Madison. G.W. Feyereisen, USDA-ARS, Soil and Water Management Research Unit, St Paul., MN. *Corresponding author: (peter.vadas@ars.usda.gov), 608-890-0069 (phone), 608-890-0076 (fax).

Abstract

Agricultural nutrient management is an issue due to nitrogen (N) and phosphorus (P) losses from fields and water quality degradation. Better information is needed on the risk of nutrient loss in runoff from dairy manure applied in winter. We investigated the effect of temperature on nutrient release from liquid and semi-solid manure to water, and of manure quantity and placement within a snowpack on nutrient release to melting snow. Temperature did not affect manure P and ammonium-N (NH_4) release during water extraction. Manure P release, but not NH_4-N release, was significantly influenced by the water-to-manure solids extraction ratio. During snowmelt, manure P release was not significantly affected by manure placement in the snowpack, and the rate of P release decreased as application rate increased. Water extraction data can reliably estimate P release from manure during snowmelt; however, snowmelt water interaction with manure of greater solids content and subsequent P release appears incomplete compared to liquid manures. Manure NH_4-N released during snowmelt was statistically the same regardless of application rate. For the semi-solid manure, NH_4-N released during snowmelt increased with the depth of snow covering it, most~~ly~~ likely due to reduced NH_3 volatilization. For the liquid manure, there was no effect of manure placement within the snowpack on NH_4-N released during snowmelt. Water extraction data can also reliably estimate manure NH_4-N release during snowmelt as long as NH_3 volatilization is accounted for with liquid manures for all placements in a snowpack and semi-solid manures applied on top of snow.

Agricultural nutrient management continues to be an important area of scientific research and policy development due to concerns over N and P losses in surface runoff from farm fields and subsequent water quality degradation (Carpenter et al., 1998; Parris, 2011). Research has consistently shown that surface manure application to fields without incorporation can be a significant source of N and P loss (Daniel et al., 1998; Kleinman and Sharpley, 2003; Vadas et al., 2007). In many northern U.S. states, as well as Canadian provinces and northern European countries, winter application of dairy manure is common because it reduces the need for expensive manure storage, allows time for manure spreading when there are fewer on-field activities, and potentially reduces soil compaction from heavy equipment if soil is frozen (Srinivasan et al., 2006). Because soils are frozen, winter-applied dairy manure is typically surface applied and left unincorporated. This fact, combined with regular and significant runoff from snowmelt and rain-on-snow events, has prompted many states to restrict winter spreading of dairy manure (Srinivasan et al., 2006), including relatively new rules in Iowa (http://www.iowadnr.gov/About-DNR/DNR-News-Releases/ArticleID/1096). However, there has been relatively little research on nutrient loss from winter applied manure as support for restrictions, especially compared to research on manure nutrient loss during non-winter periods (see citations below).

The potential for manure nutrient runoff during winter is complex and can vary due to infiltration, runoff, erosion, and nutrient cycling processes, all of which are sensitive to air temperatures and frozen soil conditions. Nutrient loss may also vary with manure spreading practices, especially relative to manure placement beneath or on top of snow and the effect of manure on rates of snow melt (Kongoli and Bland, 2002). Detailed studies of soil and manure interactions and the hydrological processes that affect nutrient transport under winter conditions are limited. Most studies have been observational with mixed results regarding the degree to which winter manure application increases the risk of nutrient runoff relative to manure application in other seasons.~~.~~ A majority of research was conducted before 1980 (Converse et al., 1976; Steenhuis et al., 1981; Young and Mutchler, 1976; Young and Holt, 1977; Klausner et al., 1976; Phillips et al., 1981). While there has been some more recent research (Hansen et al., 2000; Komiskey et al., 2011; Lewis and Makarewicz, 2009; Owens et al., 2011; Ulen, 2003), it was observational at the field-scale or larger, and did not provide data on liquid manures. The review paper of Srinivasan et al. (2006) details the results of most of these studies. Only the recent research of Williams et al. (2011; 2012b, a) has investigated winter processes at the controlled lab scale. Overall, a process-level understanding of nutrient cycling and transport processes associated with winter manure application is lacking, especially for liquid manures.

Our ~~major research~~ goal is to ~~investigate and~~ improve the understanding and modeling of biochemical and physical processes controlling frozen-soil and snowmelt infiltration, runoff, and nutrient loss from soil and winter-applied dairy manure~~. We are addressing this goal~~ through a series of lab and field-plot scale experiments. Lab experiments, such as the ones reported here, ~~are designed to~~ investigate specific processes under controlled conditions at small scales rather than under variable weather at field scales, which combined can make it difficult to identify relative importance of multiple processes. The specific objectives in the current lab experiments were to 1) investigate if less P and NH_4 are released from manure to water due to low temperatures that would occur during snowmelt (as compared to rain events in non-winter periods); 2) investigate the effect of dairy manure solids content, application amount, and placement within a snowpack on P and NH_4 release to melting snow; and 3) determine if relationships from Objective 1 can reliably predict nutrient release from manure during snowmelt in Objective 2.

Formatted: Indent: First line: 0"

Materials and Methods

Manure Extraction Experiments at Different Temperatures

We collected three dairy manures from Holstein lactating cows: i) a liquid manure at the University of Wisconsin cattle research center in Arlington, WI (Arlington liquid); ii) a semi-solid manure at the USDA Dairy Forage Research Center (DFRC semi-solid) farm in Prairie du Sac, WI; and iii) a semi-solid manure from a commercial farm in Minnesota (MN manure). The Arlington liquid manure was from a storage lagoon and had a solids content of 4.6% as determined gravimetrically after drying at 65^{o}C. Manure in the lagoon was from a barn flush system where bedding sand had been separated by gravity settling. On a dry-weight basis, total N content was 77.6 g kg^{-1}, and total P content was 11.0 g kg^{-1}. The DFRC (12.6% solids) and MN (11.6% solids) semi-solid manures were both collected from the floor of free-stall barns at the point of mechanical consolidation. For the DFRC manure, dry-weight-basis total N content was 28.0 g kg^{-1}, and total P content was 5.3 g kg^{-1}. For the MN manure, dry-weight-basis total N content was 43.8 g kg^{-1}, and total P content was 9.0% g kg^{-1}. Manures were stored at 4^{o}C when not in use.

We conducted a series of manure extractions with water at different temperatures to investigate if cold temperatures that occur during snowmelt reduce nutrient release from manure compared to warmer temperatures during non-winter rain events. We conducted all extractions in triplicate. Our procedures followed those of Kleinman et al. (2002) and Vadas and

Kleinman (2006) where fresh manure was shaken with deionized water for 1 h at different extraction ratios (cm^3 g^{-1}, dry weight equivalent). Our extraction ratios included 50:1, 100:1, 250:1, and 500:1, and temperatures included 22, 15, 10, and 5^{o}C. The MN manure was also extracted at 1^{o}C. For extractions, we weighed manure and water into separate flasks, placed them into a temperature-controlled shaker and let them equilibrate to the desired temperature for at least 24 h without shaking. We then combined the water and manure, shook the mixtures for 1 h, and filtered them through 0.45µm filters. We analyzed the filtered samples for dissolved reactive P (DRP) colorimetrically (Murphy and Riley, 1962) on a spectrophotometer, and for NH_4–N and NO_3–N on a Lachat automated analyzer (Hach Company, Loveland, CO) using QuickChem Methods 12-107-06-2-A (ammonium) and 12-107-04-1-B (nitrate). Throughout the experiments, NO_3–N concentrations in manure extractions and snowmelt leachings (see below) were negligible, so we do not present data for this N form.

Snowmelt Leaching Experiments

We designed these experiments to investigate nutrient~~s~~ release from manure to melting snow water. This is the first step in understanding and modeling potential manure nutrient transport in runoff. We therefore conducted experiments with snow and manure only, in the absence of underlying soil. We used only the Arlington liquid manure and DFRC semi-solid manure for these leaching experiments. We conducted experiments in triplicate using 15-cm diameter funnels that had flat bottoms and a series of small drainage holes. We collected natural snow and stored it frozen until use. We added snow and manure to funnels to achieve three rates of manure, and three manure placements in a snowpack, which were below snow, between two equivalent snow layers, and on top of snow. For the liquid manure, we added a snow equivalent of 1400 mL of water and manure at three wet-weight amounts of 98, 197 and 394 g. This achieved a relatively wide range of liquid (including snow and manure liquid) to manure dry matter ratios of 96, 174, and 331 $cm^3 g^{-1}$ (Table 4). For the semi-solid manure, we added a snow equivalent of 1250 mL of water and manure at wet-weight rates of 32, 68 and 136 g. This achieved liquid to manure dry matter ratios of 74, 144, and 315 $cm^3 g^{-1}$ (Table 4). For each funnel, we froze a piece of acid-washed, nylon screen in 30 mL of deionized water and placed the screen in the funnel before adding any manure or snow. This prevented any immediate loss of manure through funnels before snowmelt began. When assembled, we placed all funnels in a cold room ~~of about~~at approximately 4°C and allowed snow to melt, which took between 44 to 58 h. During melt, we collected all leachate in increments of ~~every~~ 250-300 mL. We filtered and analyzed all samples for NH_4 and P as described above.

Statistical Analysis

We used the general linear model of SAS (SAS Version 9.4) along with Tukey's mean separation to conducted a statistical analysis of results. For the water extraction experiment, variables of DRP and NH_4-N, total treatment sums of squares (SS) for the fixed effects in the ANOVA were partitioned into partial SS associated with the three manure types, four extraction ratios, five temperatures, and all their two-way and three-way treatment interactions. We used partial SS to determine the percentage of total DRP and NH_4-N associated with each treatment effect or treatment interaction. Treatment differences discussed in the text were significant at the 0.05 probability level. We conducted a similar statistical analysis for the funnel leaching experiments, where fixed effects were the two manure types, three application rates, three placements in the snowpack, and all their two-way and three-way treatment interactions.

Results and Discussion

Manure Extraction Experiments

Throughout the discussion, we refer to DRP analyzed in manure extractions as water extractable P (WEP) to be consistent with terminology in previous studies on manure P extractability (Kleinman et al., 2002; Vadas and Kleinman, 2006; Kleinman et al., 2005). Figure 1 shows results for manure WEP (mg kg^{-1} dry weight equivalent) for the three dairy manures as a function of extraction ratio and temperature. Statistical analysis indicated that only extraction ratio had a significant effect on WEP, and explained 60% of its variability (Table 1). This was true for WEP expressed on a mass basis (mg kg^{-1} dry weight equivalent) or as a percent of total P in the manure. Manure type and the manure by extraction ratio interaction each explained 16% of WEP variability, but were not statistically significant. Across all three manures, temperature did not significantly affect WEP, even though there was less WEP from the Arlington liquid manure as temperature decreased from 22^{o}C to 10^{o}C, with no further decrease less than 10^{o}C. This suggests cold temperatures do not affect P release from manure substantially enough that models need to account for the variable (Bechmann et al., 2005).

Figure 2 shows results for water extractable manure NH_4-N as a function of extraction ratio and temperature. Statistical analysis showed that only manure type had a significant effect on extractable NH_4-N, and explained 98% of the data variability (Table 1). There was greater extractable NH_4-N for the liquid manure than the semi-solid manures, which did not differ from each other. While this statistical effect of manure type was true on a mass basis (mg kg^{-1} dry weight equivalent), it was not true for NH_4-N expressed as a percent of total N in manure. Since total N content varied from 28.0 to 77.6 g kg^{-1} across manures, comparing data as a percent of total N may be more equitable. Given that, Figure 2 shows that manure NH_4-N release to water was fairly rapid and complete regardless of temperature, extraction ratio, or manure type. Good (2002) also observed no effect of extraction ratio on manure NH_4-N release. This suggests that models do not need to account for these variables when estimating NH_4-N release from manure during snowmelt.

Phosphorus Dynamics during Snowmelt Leaching

In all experiments, DRP concentrations in snowmelt water in the absence of manure were less than 0.05 mg L^{-1}. Results in Figures 3 and 4 show that DRP concentrations in incremental leachate for both the liquid manure and the DFRC semi-solid manure increased as snowmelt progressed. These data are consistent with our lab extraction data that DRP release is a function of how much water interacts with manure. Thus during snowmelt when liquid water interaction with manure is gradual, DRP release is more likely to increase as snowmelt proceeds and leads to interaction with more water (Kleinman et al., 2002).

Table 3 presents cumulative manure DRP released (mg) for both the liquid and semi-solid manures over the entire snowmelt period. Statistical analysis in Table 2 shows that on a mass basis (mg) there was no effect of manure type, placement in the snowpack, or application rate on cumulative DRP released. However, when expressed as a percent of total manure P applied, there was an effect of application rate on cumulative DRP released (Table 2). ~~This means that~~Thus, the proportion of applied manure total P that leached decreased as application rate increased. The three manure application rates during snowmelt represented about 50, 100, and 200 mg applied total P for the liquid manure and 21, 45, and 91 mg for the DFRC semi-solid manure for the high, medium, and low application rates, respectively (Table 4). Therefore, the amount of manure DRP leached during snowmelt was about 5, 9, and 17% of total P applied for the high, medium, and low application rates for both manures. These results are consistent with our lab extraction data showing that P leaching is a function of the water:solids extraction ratio and that a greater percentage of manure P is released at greater ratios (Vadas et al., 2004; Vadas et al., 2005). In the snowmelt leaching experiments, as the amount of applied manure increased, the ratio of snow water to manure solids (equivalent to extraction ratio during the water extraction experiments) decreased, and thus the percentage of applied P that was released also decreased.

There was no significant effect of manure placement within the snowpack on cumulative DRP released (Tables 2 and 3). Young and Mutchler (1976) suggested that manure applied below snow may have greater potential to interact with liquid snowmelt water and lose more nutrients in runoff. However, in controlled laboratory experiments using soil boxes, Williams et al. (2011) found less P loss in runoff from manure applied below snow compared to on top of or within snow and suggested this was because manure remained frozen below snow (due to influence of frozen soil) and was less susceptible to P loss. Phosphorus loss in runoff was the same for manure applied on top of or within snow. Our experiments did not have underlying soil and are not strictly comparable to these runoff studies. However, our data are consistent with those of Williams et al. (2011) for manure applied on top of or within snow, and suggest that snowmelt water interaction with manure and release of P, and thus potential P loss in snowmelt runoff, is functionally similar regardless of where manure is in the snowpack. Instead, site snowmelt dynamics, degree of snowmelt water interaction with manure, and runoff hydrology are likely more dominant mechanisms controlling manure P release during snowmelt and potential loss in runoff than manure placement in the snowpack (Kongoli and Bland, 2002). This suggests nutrient runoff models do not need to account for manure placement in a snowpack for P.

Vadas et al. (2004; 2005) showed that manure water extraction data such as those in Figure 1 can be used to reliably estimate how much DRP is leached from manure during a rain event. The equation used in that research to estimate DRP leached from manure by rain was:

$$\text{DRP release} = [1.2W/(W + 73.1)](\text{manure WEP}) \qquad [1]$$

where W is the water to manure extraction ratio (cm^3 g^{-1}), WEP is the manure DRP that is extracted (in mass units such as mg or mg kg^{-1}) at a W of 250:1 over 1 h, and DRP release is in the same units as WEP. Equation [1] fit well to the lab extraction data for the DFRC semi-solid manure in Figure 1 ($r^2 = 0.70$), so we applied Eq. [1] to see if it could reliably estimate DRP release from manure during our snowmelt leaching experiments. For the semi-solid manure, manure solids application rates and W values during snowmelt leaching are in Table 4. We estimated a manure WEP of 1560 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1. Applying Eq. [1] resulted in estimated DRP release amounts of 16.1, 10.6, and 6.1 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding measured rates as averaged across manure placements in snow were 4.7, 4.5, and 3.7 mg for high, medium, and low application rates (Table 3).

Clearly, less DRP was leached from the semi-solid manure during snowmelt than Eq. [1] would estimate. If we assume that the basic leaching processes represented by Eq. [1] still applied, underestimated DRP leaching suggests that not all the snowmelt water interacted with manure and that W as applied in Eq. [1] should have been less. In fact, the degree to which measured DRP release was less than that estimated by Eq. [1] was consistent. We calculated that if only 20% of snowmelt water actually interacted with manure, then Eq. [1] W values would be 15, 29, and 63 cm^3 g^{-1}; and corresponding estimated DRP release would be 4.7, 4.5, and 3.5 mg, for the high, medium, and low application rates, respectively. These estimated DRP release values are similar to measured values (Table 3).

Overall, our snowmelt leaching and water extraction data results suggest that for semi-solid manures Eq. [1] can be used in models to estimate DRP release from manure during snowmelt, and that DRP release is not a function of temperature or manure placement in a snowpack during snowmelt. However, the amount of snowmelt water that actually interacts with the manure and subsequent DRP release is significantly less compared to water interaction with manure during a rain event. During modeling research using Eq. [1] to simulate P loss in runoff from winter applied manure, Vadas et al. (2017) found that field scale runoff data also indicated incomplete interaction of snowmelt water with solid beef manure. Clearly, this possibility of incomplete snowmelt water interaction with solid manure and reduced DRP release deserves further investigation, especially as we could find no ~~information in the~~ literature on this~~e~~ topic.

For the Arlington liquid manure, Eq. [1] did not effectively describe the lab WEP extraction data in Figure 1 ($r^2 = 0.05$). The reason for this is unknown, but could be related to manure P mineralogy, which can be a function of animal diet or bedding material (Pagliari, 2011). The liquid manure WEP extraction data instead exhibited a linear increase in manure WEP with W, while Eq. [1] is nonlinear. Therefore, we used data from Figure 1 (as averaged across all temperatures) to represent DRP release from the liquid manure as:

$$\text{DRP release} = (0.005\ W - 0.253)(\text{manure WEP}) \qquad r^2=0.96 \qquad [2]$$

For the liquid manure, manure solids application amounts and W values are in Table 4. We estimated a manure WEP of 1840 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1. Applying Eq. [2] resulted in manure DRP release amounts of 8.4, 10.3 and 7.7 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding measured rates were 7.8, 8.0, and 8.6 mg for the high, medium, and low application rates (Table 3). Similar to the DFRC semi-solid manure, these liquid manure results suggest that lab water extraction data can be used to estimate DRP release from manure during snowmelt, without considering temperature or manure placement in a snowpack during snowmelt. Data also demonstrate that when estimating DRP release from a liquid manure during snowmelt, incomplete snowmelt water interaction with manure does not need to be considered. This may be because liquid manure is more evenly distributed and absorbed into the snowpack than a semi-solid manure, and thus has a potential for greater snowmelt interaction. As before, this possibility of more complete snowmelt interaction with liquid manure but incomplete snowmelt water interaction with more solid manure deserves further investigation.

Nitrogen Dynamics during Snowmelt Leaching

In all leaching experiments, NH_4-N concentrations in snow water without manure were less than 0.30 mg L^{-1}. Results in Figures 3 and 4 show that NH_4-N concentrations in incremental leachate water from both the liquid and semi-solid manures decreased as snowmelt progressed. These data are consistent with our lab extractions that showed NH_4-N release is not a function of how much water interacts with manure. Thus during snowmelt, NH_4-N release would be expected to be rapid even with only low amounts of snowmelt water (first flush phenomenon).

Statistical analysis in Table 2 shows that only manure type had a significant effect on mass (mg) of cumulative NH_4-N leached during snowmelt (Table 3). However, when NH_4-N release was expressed as a function of total N applied in manure, no treatment variables had a significant effect on NH_4-N leached (Table 2). ~~This means that~~Thus, a similar percentage of applied total N leached from manure regardless of application rate and thus snow water:manure solids ratio. For both manures, an average of 19.2% (s.d. of 2.3%) of applied manure total N was leached.

For the semi-solid manure, although placement in the snowpack was not a significant factor (Table 2), the amount of NH_4-N leached during snowmelt consistently increased with the depth of snow covering it (Table 3). This is most likely because manure applied on top of snow, and even between snow layers, had longer direct exposure to the air above it, had greater NH_3 volatilization, and thus had less NH_4-N available for leaching loss (Williams et al., 2011; Lauer et al., 1976). Steenhuis et al. (1979) observed about 35% greater NH_3 volatilization from a dairy manure (16% solids) placed on top of a snow pack compared to below a 10cm snowpack over four days. Similarly, we observed about 30% more NH_4-N in leachate from our semi-solid manure when manure was below the snowpack compared to on top. An average of 20.6% (s.d. of 1.7%), 18.6% (s.d. of 1.5%), and 13.5% (s.d. of 0.7%) of applied manure total N was leached as NH_4-N for the manure below, in between, and on top of snow, respectively. For the liquid manure at a given manure application rate, there was no trend of manure placement within the snowpack on NH_4-N leached during snowmelt (Table 3). An average of 20.9% (s.d. of 2.3%) of manure total N was leached as NH_4-N. Therefore, our data suggest that NH_3 volatilization may not vary as a function of placement in a snowpack for liquid manure.

Similar to P, we investigated if our water extraction data could reliably estimate NH_4-N release from manure during snowmelt. Combining the data from all three manures in Figure 2, we developed the equation below (similar to Eqs. [1] and [2]):

$$NH_4 \text{ release} = (0.0004\ W - 0.758)(\text{manure } NH_4\text{-N}) \qquad r^2=0.50 \qquad [3]$$

Solids application rates and W values during snowmelt leaching are in Table 4. We estimated manure NH_4-N from maximum amounts extracted during water extractions (Figure 2). Applying Eq. [3] for the semi-solid manure resulted in predicted NH_4-N release of 86.3, 44.7, and 22.8 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding average measured NH_4-N release rates when manure was applied below or between snow layers were 88.6, 45.7, and 24.0 mg (Table 3). Therefore, Eq. [3] reliably estimated manure NH_4-N release for these two manure placements. However, corresponding measured NH_4-N release rates when manure was applied on top of snow was 64.3, 30.7, and 15.9 mg (Table 3). Therefore, Eq. [3] over-estimated manure NH_4-N release for this manure placement. It is reasonable to assume that overprediction is due to unaccounted for NH_3 volatilization from manure applied on top of snow. In fact, if we assume a NH_3 volatilization rate of 35% for manure applied on top of snow, as reported by Steenhuis et al. (1979) (i.e., 35% less manure NH_4-N available to leach), predicted NH_4-N release in snowmelt would be 56.1, 29.0, and 14.8 mg, which is close to measured values. Converse to P, these data also demonstrate that when estimating manure NH_4-N release from a semi-solid manure during snowmelt, incomplete snowmelt water interaction with manure does not need to be considered. This may be because NH_4-N release is much less sensitive to the amount of water that interacts with manure (Fig. 2).

For the liquid manure, manure solids application rates and W values are in Table 4. Applying Eq. [3] resulted in predicted NH_4-N release amounts of 479.0, 239.5, and 112.7 mg for the high, medium, and low application rates, respectively (Table 4). Corresponding measured NH_4-N release rates were clearly much less at 266.7, 150.1, and 79.5 mg (Table 3). If we attribute overprediction to NH_3 volatilization from applied manure, a volatilization rate of 35% of applied manure NH_4-N would result in predicted NH_4-N release during snowmelt of 282.2, 146.6, and 78.9 mg, which agreed well with measured rates. Overall, our data suggest that water extraction data can be used to reliably estimate manure NH_4-N release during snowmelt without having to consider temperature or NH_3 volatilization if a semi-solid to solid manure is covered by snow. However, NH_3 volatilization needs to be accounted for with liquid manures at all placements in a snowpack and a semi-solid manure applied on top of snow.

Conclusions

Our lab-scale experiments suggest that temperature may not significantly influence manure WEP and NH_4-N release to water. Also, manure WEP release, but not NH_4-N release, to water will be influenced by the water-to-manure solids ratio. Manure placement within a snowpack may not significantly influence snowmelt interaction with manure and leaching of DRP. For semi-solid manures, the amount of NH_4-N leached during snowmelt can increase with the depth of snow covering it. This is mostly likely because manure applied on top of snow, and even between snow layers, has greater NH_3 volatilization and thus less NH_4-N available for leaching loss. For liquid manures, NH_3 volatilization may not vary as a function of placement in a snowpack, but liquid manures applied to snow will have greater NH_3 volatilization than more solid manures unless the solid manures are applied on top of snow and have significant NH_3

volatilization. Finally, lab water extractions can be used to reliably estimate manure NH_4-N release during snowmelt, but variations in NH_3 volatilization need to be accounted for with liquid manures at all placements in a snowpack and a semi-solid manure applied on top of snow. Lab water extractions can also be used to estimate DRP release from manure during snowmelt; but for semi-solid to solid manures, the amount of snowmelt water that actually interacts with the manure and subsequent WEP release is significantly less compared to water interaction with manure during a rain event. The same is not true for liquid manures applied to snow. This may be because liquid manure is more evenly distributed and absorbed into a snowpack than a semi-solid manure, and thus has a greater potential for complete snowmelt interaction. This possibility of more complete snowmelt interaction with liquid manures but incomplete snowmelt water interaction with more solid manure during DRP release deserves further investigation, especially as a function of a range of manure solids content. Overall, our data will help improve simulation models that can be applied to explore the management and environmental implications of winter manure spreading and variable winter runoff conditions.

References

Bechmann, M.E., P.J.A. Kleinman, A.N. Sharpley, and L.S. Saporito. 2005. Freeze-thaw effects on phosphorus loss in runoff froin manured and catch-cropped soils. J. Environ. Qual. 34:2301-2309.
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. Ecol. Appl. 8:559-568.
Converse, J.C., G.D. Bubenzer, and W.H. Paulson. 1976. Nutrient Losses in Surface Runoff from Winter Spread Manure. Trans. ASAE 19:517-519.
Daniel, T.C., A.N. Sharpley, and J.L. Lemunyon. 1998. Agricultural phosphorus and eutrophication: A symposium overview. J. Environ. Qual. 27:251-257.
Good, L.W. 2002. Mechanisms controlling phosphorus loss to water from animal manures and manure-amended soils. Ph.D. diss., Univ. Wisconsin, Madison.
Hansen, N.C., S.C. Gupta, and J.F. Moncrief. 2000. Snowmelt runoff, sediment, and phosphorus losses under three different tillage systems. Soil Till Res 57:93-100.

Klausner, S.D., P.J. Zwerman, and D.F. Ellis. 1976. Nitrogen and Phosphorus Losses from Winter Disposal of Dairy Manure. J. Environ. Qual. 5:47-49.

Kleinman, P.J.A., and A.N. Sharpley. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. J. Environ. Qual. 32:1072-1081.

Kleinman, P.J.A., A.N. Sharpley, A.M. Wolf, D.B. Beegle, and P.A. Moore. 2002. Measuring water-extractable phosphorus in manure as an indicator of phosphorus in runoff. Soil Sci. Soc. Am. J. 66:2009-2015.

Kleinman, P.J.A., A.M. Wolf, A.N. Sharpley, D.B. Beegle, and L.S. Saporito. 2005. Survey of water-extractable phosphorus in livestock manures. Soil Sci. Soc. Am. J. 69:701-708.

Komiskey, M.J., T.D. Stuntebeck, D.R. Frame, and F.W. Madison. 2011. Nutrients and sediment in frozen-ground runoff from no-till fields receiving liquid-dairy and solid-beef manures. J. Soil Water Conserv. 66:303-312.

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

Lauer, D.A., D.R. Bouldin, and S.D. Klausner. 1976. Ammonia Volatilization from Dairy Manure Spread on Soil Surface. J. Environ. Qual. 5:134-141.

Lewis, T.W., and J.C. Makarewicz. 2009. Winter application of manure on an agricultural watershed and its impact on downstream nutrient fluxes. J Great Lakes Res 35:43-49.

Murphy, J., and J.P. Riley. 1962. A Modified Single Solution Method for Determination of Phosphate in Natural Waters. Anal. Chim. Acta 27:31-36.

Owens, L.B., J.V. Bonta, M.J. Shipitalo, and S. Rogers. 2011. Effects of Winter Manure Application in Ohio on the Quality of Surface Runoff. J. Environ. Qual. 40:153-165.

Pagliari, P.H. 2011. Investigation of inorganic and organic phosphorus in animal manure and their effects on soil test phosphorus. Ph.D. diss., Univ. Wisconsin, Madison.

Parris, K. 2011. Impact of Agriculture on Water Pollution in OECD Countries: Recent Trends and Future Prospects. Int J Water Resour D 27:33-52.

Phillips, P.A., J.L.B. Culley, F.R. Hore, and N.K. Patni. 1981. Pollution Potential and Corn Yields from Selected Rates and Timing of Liquid Manure Applications. Trans. ASAE 24:139-144.

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 Water Conserv. 61:200-209.

Steenhuis, T.S., G.D. Bubenzer, and J.C. Converse. 1979. Ammonia Volatilization of Winter Spread Manure. Trans. ASAE 22:152-&.

Steenhuis, T.S., G.D. Bubenzer, J.C. Converse, and M.F. Walter. 1981. Winter-Spread Manure Nitrogen Loss. Trans. ASAE 24:436-442.

Ulen, B. 2003. Concentrations and transport of different forms of phosphorus during snowmelt runoff from an illite clay soil. Hydrological Processes 17:747-758.

Vadas, P.A., L.W. Good, W.E. Jokela, K.G. Karthikeyan, F.J. Arriaga, and M. Stock. 2017. Quantifying the impact of seasonal and short-term manure application decisions on phosphorus loss in surface runoff. J. Envrion. Qual. 46:doi:10.2134/jeq2016.2106.0220.

Vadas, P.A., B.E. Haggard, and W.J. Gburek. 2005. Predicting dissolved phosphorus in runoff from manured field plots. J. Environ. Qual. 34:1347-1353.

Vadas, P.A., R.D. Harmel, and P.J.A. Kleinman. 2007. Transformations of soil and manure phosphorus after surface application of manure to field plots. Nutr. Cycl. Agroeco. 77:83-99.

Vadas, P.A., and P.J.A. Kleinman. 2006. Effect of methodology in estimating and interpreting water-extractable phosohorus in animal manures. J. Environ. Qual. 35:1151-1159.

Vadas, P.A., P.J.A. Kleinman, and A.N. Sharpley. 2004. A simple method to predict dissolved phosphorus in runoff from surface-applied manures. J. Environ. Qual. 33:749-756.

Williams, M.R., G.W. Feyereisen, D.B. Beegle, and R.D. Shannon. 2012a. Soil Temperature Regulates Nitrogen Loss from Lysimeters Following Fall and Winter Manure Application. Trans. ASABE 55:861-870.

Williams, M.R., G.W. Feyereisen, D.B. Beegle, and R.D. Shannon. 2012b. Soil Temperature Regulates Phosphorus Loss from Lysimeters Following Fall and Winter Manure Application. Trans. ASABE 55:871-880.

Williams, M.R., G.W. Feyereisen, D.B. Beegle, R.D. Shannon, G.J. Folmar, and R.B. Bryant. 2011. Manure Application under Winter Conditions: Nutrient Runoff and Leaching Losses. Trans. ASABE 54:891-899.

Young, R.A., and R.F. Holt. 1977. Winter-Applied Manure - Effects on Annual Runoff, Erosion, and Nutrient Movement. J. Soil Water Conserv. 32:219-222.

Young, R.A., and C.K. Mutchler. 1976. Pollution Potential of Manure Spread on Frozen Ground. J. Environ. Qual. 5:174-179.

Figure Captions

Figure 1. Manure WEP release for the Arlington liquid dairy manure and the DFRC and MN semi-solid dairy manures during water extraction experiments as a function of extraction temperature and extraction ratio (water to manure solids, cm^3 g^{-1}). ~~Letters~~ Bars indicate ~~a significant effect of temperature (p=0.05) at that specific extraction ratio only~~the standard deviation of the means.

Figure 2. Manure NH_4-N release for the Arlington liquid dairy manure and the DFRC and MN semi-solid dairy manures during water extraction experiments as a function of extraction temperature and extraction ratio (water to manure solids, cm^3 g^{-1}). Bars indicate the standard deviation of the means.

~~Letters indicate a significant effect of temperature (p=0.05) at that specific extraction ratio only.~~

Figure 3. Change in dissolved P and NH_4-N concentrations in snowmelt water with increasing leachate volume during snowmelt leaching experiments with the Arlington liquid dairy manure applied at three different rates. Data for a given rate are averaged across manure placements in the snowpack. Bars indicate the standard deviation of the means.

Figure 4. Change in dissolved P and NH_4-N concentrations in snowmelt water with increasing leachate volume during snowmelt leaching experiments with the DFRC semi-solid dairy manure applied at three different rates. Data for a given rate are averaged across manure placements in the snowpack. Bars indicate the standard deviation of the means.

Table 1. ANOVA for effects of manure, extraction ratio, and temperature on manure WEP and NH_4-N extracted during water extraction experiments. Data are presented for concentrations (mg kg^{-1}) as well percent of total P or total N in manure.

Source of Treatment Variation		WEP		Percent of Total P		NH_4-N		Percent of Total N	
	Df	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt
Manure	2	0.1471	16.4	0.1917	17.3	0.0017	97.7	0.1376	90.9
Ratio	3	0.0044	58.2	0.0077	62.8	0.9792	1.2	0.9645	5.9
Temperature	4	0.9553	2.8	0.9821	2.0	1.0000	0.1	1.0000	0.2
Manure * Ratio	6	0.6822	16.0	0.8775	11.5	1.0000	0.4	1.0000	0.8
Manure * Temperature	6	0.9952	2.7	0.9964	2.9	1.0000	0.3	1.0000	1.2
Ratio * Temperature	12	1.0000	0.9	1.0000	0.7	1.0000	0.1	1.0000	0.5
Manure * Ratio * Temperature	18	1.0000	2.9	1.0000	2.9	1.0000	0.1	1.0000	0.6

Table 2. ANOVA for effects of manure, extraction ratio, and temperature on manure DRP and NH_4-N leached during snowmelt leaching experiments. Data are presented for mass (mg) as well percent of total P or total N applied to funnels ~~in~~ as manure.

Source of Treatment Variation		DRP		Percent of Total P		NH_4-N		Percent of Total N	
	Df	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt	P-Value	% Trt
Manure	1	0.1006	76.7	0.6992	1.8	0.0254	53.0	0.5713	31.1
Placement	2	0.9632	1.9	0.9981	0.0	0.9857	0.3	0.8993	19.9
Rate	2	0.9928	0.4	0.0423	87.0	0.1710	34.8	0.9286	13.9
Manure * Placement	2	0.8219	10.2	0.7860	5.6	0.9903	0.2	0.9166	16.4
Manure * Rate	2	0.9473	2.8	0.9804	0.5	0.5693	10.4	0.9896	2.0
Placement * Rate	4	0.9991	2.1	0.9999	0.3	0.9993	0.6	0.9992	7.4
Manure * Placement * Rate	4	0.9931	6.0	0.9787	4.9	0.9989	0.8	0.9986	9.4

Table 3. Cumulative ~~M~~manure DRP and NH_4-N release (mg) for the Arlington Liquid and DFRC semi-solid dairy manures during snowmelt experiments as a function of manure application rate (Low, Medium, High) and manure placement within a snowpack (under snow, between snow layers, and on top of snow). Values in parentheses are DRP and NH_4-N release expressed as percentages of total P and total N applied as manure.

Rate	Under	Between	Top	Under	Between	Top
		DRP			NH_4-N	
	mg	mg	mg	mg	mg	mg
			Liquid Manure			
(Low	6.5 (13.0)	9.0 (18.0)	10.2 (20.4)	74.2 (21.1)	89.6 (25.5)	74.8 (21.3)
Medium	6.6 (6.6)	9.0 (9.0)	8.4 (8.4)	145.6 (20.7	164.5 (23.4)	140.1 (19.9)
High	7.0 (3.5)	9.2 (4.6)	7.1 (3.6)	279.8 (19.9)	260.7 (18.5)	259.6 (18.9)
			Semi-solid Manure			
Low	4.7 (22.4)	3.4 (16.2)	2.8 (13.3)	25.1 (22.4)	22.8 (20.4)	15.9 (14.2)
Medium	5.4 (12.0)	3.8 (8.4)	4.3 (9.6)	49.7 (20.8)	41.8 (17.5)	30.7 (12.8)
High	5.2 (5.7)	4.3 (4.7)	4.6 (5.1)	90.5 (18.9)	86.7 (18.1)	64.3 (13.4)

Formatted Table

Table 4. Data for manure solids applied, water:solids ratio, manure total P and N applied, and predicted DRP and NH_4-N release for both the liquid and semi-solid manures during the snowmelt leaching experiments.

Rate	Manure Solids Applied[1]	Water:Solids Ratio (W)[2]	Manure Total P Applied	Manure Total N Applied	Predicted DRP Release[3]	Predicted NH_4-N Release[4]
	g	cm^3 g^{-1}	mg	mg	mg	mg
			Liquid Manure			
Low	4.5	331.2	49.9	352.3	8.4	78.9
Medium	9.1	174.0	99.9	704.7	10.3	146.6
High	18.2	96.4	199.8	1409.4	7.7	282.2
			Semi-solid Manure			
Low	4.0	316.0	21.3	112.7	6.1	22.8
Medium	8.6	144.0	45.3	239.5	10.6	44.7
High	17.1	74.0	90.7	479.0	16.1	86.3

[1] Dry weight equivalent

[2] Includes water in manure and 1250 mL snow water for semi-solid manure and 1400 mL for liquid manure

[3] Predictions use Eq. [1] for semi-solid manure and Eq. [2] for liquid manure

[4] Predictions use Eq. [3]