

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

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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.

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

64 The potential for manure nutrient runoff during winter is complex and can vary due to
65 infiltration, runoff, erosion, and nutrient cycling processes, all of which are sensitive to air
66 temperatures and frozen soil conditions. Nutrient loss may also vary with manure spreading
67 practices, especially relative to manure placement beneath or on top of snow and the effect of
68 manure on rates of snow melt (Kongoli and Bland, 2002). Detailed studies of soil and manure
69 interactions and the hydrological processes that affect nutrient transport under winter conditions

70 are limited. Most studies have been observational with mixed results regarding the degree to
71 which winter manure application increases the risk of nutrient runoff relative to manure
72 application in other seasons. A majority of research was conducted before 1980 (Converse et al.,
73 1976; Steenhuis et al., 1981; Young and Mutchler, 1976; Young and Holt, 1977; Klausner et al.,
74 1976; Phillips et al., 1981). While there has been some more recent research (Hansen et al.,
75 2000; Komiskey et al., 2011; Lewis and Makarewicz, 2009; Owens et al., 2011; Ulen, 2003), it
76 was observational at the field-scale or larger, and did not provide data on liquid manures. The
77 review paper of Srinivasan et al. (2006) details the results of most of these studies. Only the
78 recent research of Williams et al. (2011; 2012b, a) has investigated winter processes at the
79 controlled lab scale. Overall, a process-level understanding of nutrient cycling and transport
80 processes associated with winter manure application is lacking, especially for liquid manures.

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

93

94 **Materials and Methods**95 **Manure Extraction Experiments at Different Temperatures**

96 We collected three dairy manures from Holstein lactating cows: i) a liquid manure at the
97 University of Wisconsin cattle research center in Arlington, WI (Arlington liquid); ii) a semi-
98 solid manure at the USDA Dairy Forage Research Center (DFRC semi-solid) farm in Prairie du
99 Sac, WI; and iii) a semi-solid manure from a commercial farm in Minnesota (MN manure). The
100 Arlington liquid manure was from a storage lagoon and had a solids content of 4.6% as
101 determined gravimetrically after drying at 65°C. Manure in the lagoon was from a barn flush
102 system where bedding sand had been separated by gravity settling. On a dry-weight basis, total N
103 content was 77.6 g kg⁻¹, and total P content was 11.0 g kg⁻¹. The DFRC (12.6% solids) and MN
104 (11.6% solids) semi-solid manures were both collected from the floor of free-stall barns at the
105 point of mechanical consolidation. For the DFRC manure, dry-weight-basis total N content was
106 28.0 g kg⁻¹, and total P content was 5.3 g kg⁻¹. For the MN manure, dry-weight-basis total N
107 content was 43.8 g kg⁻¹, and total P content was 9.0% g kg⁻¹. Manures were stored at 4°C when
108 not in use.

109 We conducted a series of manure extractions with water at different temperatures to
110 investigate if cold temperatures that occur during snowmelt reduce nutrient release from manure
111 compared to warmer temperatures during non-winter rain events. We conducted all extractions in
112 triplicate. Our procedures followed those of Kleinman et al. (2002) and Vadas and Kleinman
113 (2006) where fresh manure was shaken with deionized water for 1 h at different extraction ratios
114 (cm³ g⁻¹, dry weight equivalent). Our extraction ratios included 50:1, 100:1, 250:1, and 500:1,
115 and temperatures included 22, 15, 10, and 5°C. The MN manure was also extracted at 1°C. For

116 extractions, we weighed manure and water into separate flasks, placed them into a temperature-
117 controlled shaker and let them equilibrate to the desired temperature for at least 24 h without
118 shaking. We then combined the water and manure, shook the mixtures for 1 h, and filtered them
119 through 0.45 μ m filters. We analyzed the filtered samples for dissolved reactive P (DRP)
120 colorimetrically (Murphy and Riley, 1962) on a spectrophotometer, and for NH₄-N and NO₃-N
121 on a Lachat automated analyzer (Hach Company, Loveland, CO) using QuickChem Methods 12-
122 107-06-2-A (ammonium) and 12-107-04-1-B (nitrate). Throughout the experiments, NO₃-N
123 concentrations in manure extractions and snowmelt leachings (see below) were negligible, so we
124 do not present data for this N form.

125

126 **Snowmelt Leaching Experiments**

127 We designed these experiments to investigate nutrient release from manure to melting
128 snow water. This is the first step in understanding and modeling potential manure nutrient
129 transport in runoff. We therefore conducted experiments with snow and manure only, in the
130 absence of underlying soil. We used only the Arlington liquid manure and DFRC semi-solid
131 manure for these leaching experiments. We conducted experiments in triplicate using 15-cm
132 diameter funnels that had flat bottoms and a series of small drainage holes. We collected natural
133 snow and stored it frozen until use. We added snow and manure to funnels to achieve three rates
134 of manure, and three manure placements in a snowpack, which were below snow, between two
135 equivalent snow layers, and on top of snow. For the liquid manure, we added a snow equivalent
136 of 1400 mL of water and manure at three wet-weight amounts of 98, 197 and 394 g. This
137 achieved a relatively wide range of liquid (including snow and manure liquid) to manure dry
138 matter ratios of 96, 174, and 331 cm³ g⁻¹ (Table 4). For the semi-solid manure, we added a snow

139 equivalent of 1250 mL of water and manure at wet-weight rates of 32, 68 and 136 g. This
140 achieved liquid to manure dry matter ratios of 74, 144, and 315 cm³ g⁻¹ (Table 4). For each
141 funnel, we froze a piece of acid-washed, nylon screen in 30 mL of deionized water and placed
142 the screen in the funnel before adding any manure or snow. This prevented any immediate loss
143 of manure through funnels before snowmelt began. When assembled, we placed all funnels in a
144 cold room at approximately 4°C and allowed snow to melt, which took between 44 to 58 h.
145 During melt, we collected all leachate in increments of 250-300 mL. We filtered and analyzed all
146 samples for NH₄ and P as described above.

147

148 **Statistical Analysis**

149 We used the general linear model of SAS (SAS Version 9.4) along with Tukey's mean
150 separation to conducted a statistical analysis of results. For the water extraction experiment,
151 variables of DRP and NH₄-N, total treatment sums of squares (SS) for the fixed effects in the
152 ANOVA were partitioned into partial SS associated with the three manure types, four extraction
153 ratios, five temperatures, and all their two-way and three-way treatment interactions. We used
154 partial SS to determine the percentage of total DRP and NH₄-N associated with each treatment
155 effect or treatment interaction. Treatment differences discussed in the text were significant at the
156 0.05 probability level. We conducted a similar statistical analysis for the funnel leaching
157 experiments, where fixed effects were the two manure types, three application rates, three
158 placements in the snowpack, and all their two-way and three-way treatment interactions.

159

160 **Results and Discussion**

161 **Manure Extraction Experiments**

162 Throughout the discussion, we refer to DRP analyzed in manure extractions as water
163 extractable P (WEP) to be consistent with terminology in previous studies on manure P
164 extractability (Kleinman et al., 2002; Vadas and Kleinman, 2006; Kleinman et al., 2005). Figure
165 1 shows results for manure WEP (mg kg^{-1} dry weight equivalent) for the three dairy manures as a
166 function of extraction ratio and temperature. Statistical analysis indicated that only extraction
167 ratio had a significant effect on WEP, and explained 60% of its variability (Table 1). This was
168 true for WEP expressed on a mass basis (mg kg^{-1} dry weight equivalent) or as a percent of total P
169 in the manure. Manure type and the manure by extraction ratio interaction each explained 16% of
170 WEP variability, but were not statistically significant. Across all three manures, temperature did
171 not significantly affect WEP, even though there was less WEP from the Arlington liquid manure
172 as temperature decreased from 22°C to 10°C, with no further decrease less than 10°C. This
173 suggests cold temperatures do not affect P release from manure substantially enough that models
174 need to account for the variable (Bechmann et al., 2005).

175 Figure 2 shows results for water extractable manure $\text{NH}_4\text{-N}$ as a function of extraction
176 ratio and temperature. Statistical analysis showed that only manure type had a significant effect
177 on extractable $\text{NH}_4\text{-N}$, and explained 98% of the data variability (Table 1). There was greater
178 extractable $\text{NH}_4\text{-N}$ for the liquid manure than the semi-solid manures, which did not differ from
179 each other. While this statistical effect of manure type was true on a mass basis (mg kg^{-1} dry
180 weight equivalent), it was not true for $\text{NH}_4\text{-N}$ expressed as a percent of total N in manure. Since
181 total N content varied from 28.0 to 77.6 g kg^{-1} across manures, comparing data as a percent of
182 total N may be more equitable. Given that, Figure 2 shows that manure $\text{NH}_4\text{-N}$ release to water
183 was fairly rapid and complete regardless of temperature, extraction ratio, or manure type. Good
184 (2002) also observed no effect of extraction ratio on manure $\text{NH}_4\text{-N}$ release. This suggests that

185 models do not need to account for these variables when estimating $\text{NH}_4\text{-N}$ release from manure
186 during snowmelt.

187

188 **Phosphorus Dynamics during Snowmelt Leaching**

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

196 Table 3 presents cumulative manure DRP released (mg) for both the liquid and semi-
197 solid manures over the entire snowmelt period. Statistical analysis in Table 2 shows that on a
198 mass basis (mg) there was no effect of manure type, placement in the snowpack, or application
199 rate on cumulative DRP released. However, when expressed as a percent of total manure P
200 applied, there was an effect of application rate on cumulative DRP released (Table 2). Thus, the
201 proportion of applied manure total P that leached decreased as application rate increased. The
202 three manure application rates during snowmelt represented about 50, 100, and 200 mg applied
203 total P for the liquid manure and 21, 45, and 91 mg for the DFRC semi-solid manure for the
204 high, medium, and low application rates, respectively (Table 4). Therefore, the amount of
205 manure DRP leached during snowmelt was about 5, 9, and 17% of total P applied for the high,
206 medium, and low application rates for both manures. These results are consistent with our lab
207 extraction data showing that P leaching is a function of the water:solids extraction ratio and that

208 a greater percentage of manure P is released at greater ratios (Vadas et al., 2004; Vadas et al.,
209 2005). In the snowmelt leaching experiments, as the amount of applied manure increased, the
210 ratio of snow water to manure solids (equivalent to extraction ratio during the water extraction
211 experiments) decreased, and thus the percentage of applied P that was released also decreased.

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

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

232

$$233 \text{ DRP release} = [1.2W/(W + 73.1)](\text{manure WEP}) \quad [1]$$

234

235 where W is the water to manure extraction ratio ($\text{cm}^3 \text{g}^{-1}$), WEP is the manure DRP that is
236 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
237 the same units as WEP. Equation [1] fit well to the lab extraction data for the DFRC semi-solid
238 manure in Figure 1 ($r^2 = 0.70$), so we applied Eq. [1] to see if it could reliably estimate DRP
239 release from manure during our snowmelt leaching experiments. For the semi-solid manure,
240 manure solids application rates and W values during snowmelt leaching are in Table 4. We
241 estimated a manure WEP of 1560 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1.
242 Applying Eq. [1] resulted in estimated DRP release amounts of 16.1, 10.6, and 6.1 mg for the
243 high, medium, and low application rates, respectively (Table 4). Corresponding measured rates
244 as averaged across manure placements in snow were 4.7, 4.5, and 3.7 mg for high, medium, and
245 low application rates (Table 3).

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

252 15, 29, and 63 cm³ g⁻¹; and corresponding estimated DRP release would be 4.7, 4.5, and 3.5 mg,
253 for the high, medium, and low application rates, respectively. These estimated DRP release
254 values are similar to measured values (Table 3).

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

265 For the Arlington liquid manure, Eq. [1] did not effectively describe the lab WEP
266 extraction data in Figure 1 ($r^2 = 0.05$). The reason for this is unknown, but could be related to
267 manure P mineralogy, which can be a function of animal diet or bedding material (Pagliari,
268 2011). The liquid manure WEP extraction data instead exhibited a linear increase in manure
269 WEP with W, while Eq. [1] is nonlinear. Therefore, we used data from Figure 1 (as averaged
270 across all temperatures) to represent DRP release from the liquid manure as:

271

$$272 \text{ DRP release} = (0.005 W - 0.253)(\text{manure WEP}) \quad r^2=0.96 \quad [2]$$

273

274 For the liquid manure, manure solids application amounts and W values are in Table 4. We
275 estimated a manure WEP of 1840 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1.
276 Applying Eq. [2] resulted in manure DRP release amounts of 8.4, 10.3 and 7.7 mg for the high,
277 medium, and low application rates, respectively (Table 4). Corresponding measured rates were
278 7.8, 8.0, and 8.6 mg for the high, medium, and low application rates (Table 3). Similar to the
279 DFRC semi-solid manure, these liquid manure results suggest that lab water extraction data can
280 be used to estimate DRP release from manure during snowmelt, without considering temperature
281 or manure placement in a snowpack during snowmelt. Data also demonstrate that when
282 estimating DRP release from a liquid manure during snowmelt, incomplete snowmelt water
283 interaction with manure does not need to be considered. This may be because liquid manure is
284 more evenly distributed and absorbed into the snowpack than a semi-solid manure, and thus has
285 a potential for greater snowmelt interaction. As before, this possibility of more complete
286 snowmelt interaction with liquid manure but incomplete snowmelt water interaction with more
287 solid manure deserves further investigation.

288

289 **Nitrogen Dynamics during Snowmelt Leaching**

290 In all leaching experiments, $\text{NH}_4\text{-N}$ concentrations in snow water without manure were
291 less than 0.30 mg L^{-1} . Results in Figures 3 and 4 show that $\text{NH}_4\text{-N}$ concentrations in incremental
292 leachate water from both the liquid and semi-solid manures decreased as snowmelt progressed.
293 These data are consistent with our lab extractions that showed $\text{NH}_4\text{-N}$ release is not a function of
294 how much water interacts with manure. Thus during snowmelt, $\text{NH}_4\text{-N}$ release would be
295 expected to be rapid even with only low amounts of snowmelt water (first flush phenomenon).

296 Statistical analysis in Table 2 shows that only manure type had a significant effect on
297 mass (mg) of cumulative $\text{NH}_4\text{-N}$ leached during snowmelt (Table 3). However, when $\text{NH}_4\text{-N}$
298 release was expressed as a function of total N applied in manure, no treatment variables had a
299 significant effect on $\text{NH}_4\text{-N}$ leached (Table 2). Thus, a similar percentage of applied total N
300 leached from manure regardless of application rate and thus snow water:manure solids ratio. For
301 both manures, an average of 19.2% (s.d. of 2.3%) of applied manure total N was leached.

302 For the semi-solid manure, although placement in the snowpack was not a significant
303 factor (Table 2), the amount of $\text{NH}_4\text{-N}$ leached during snowmelt consistently increased with the
304 depth of snow covering it (Table 3). This is most likely because manure applied on top of snow,
305 and even between snow layers, had longer direct exposure to the air above it, had greater NH_3
306 volatilization, and thus had less $\text{NH}_4\text{-N}$ available for leaching loss (Williams et al., 2011; Lauer
307 et al., 1976). Steenhuis et al. (1979) observed about 35% greater NH_3 volatilization from a dairy
308 manure (16% solids) placed on top of a snow pack compared to below a 10cm snowpack over
309 four days. Similarly, we observed about 30% more $\text{NH}_4\text{-N}$ in leachate from our semi-solid
310 manure when manure was below the snowpack compared to on top. An average of 20.6% (s.d. of
311 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
312 $\text{NH}_4\text{-N}$ for the manure below, in between, and on top of snow, respectively. For the liquid
313 manure at a given manure application rate, there was no trend of manure placement within the
314 snowpack on $\text{NH}_4\text{-N}$ leached during snowmelt (Table 3). An average of 20.9% (s.d. of 2.3%) of
315 manure total N was leached as $\text{NH}_4\text{-N}$. Therefore, our data suggest that NH_3 volatilization may
316 not vary as a function of placement in a snowpack for liquid manure.

317 Similar to P, we investigated if our water extraction data could reliably estimate $\text{NH}_4\text{-N}$
318 release from manure during snowmelt. Combining the data from all three manures in Figure 2,
319 we developed the equation below (similar to Eqs. [1] and [2]):

320

$$321 \text{NH}_4 \text{ release} = (0.0004 W - 0.758)(\text{manure NH}_4\text{-N}) \quad r^2=0.50 \quad [3]$$

322

323 Solids application rates and W values during snowmelt leaching are in Table 4. We estimated
324 manure $\text{NH}_4\text{-N}$ from maximum amounts extracted during water extractions (Figure 2). Applying
325 Eq. [3] for the semi-solid manure resulted in predicted $\text{NH}_4\text{-N}$ release of 86.3, 44.7, and 22.8 mg
326 for the high, medium, and low application rates, respectively (Table 4). Corresponding average
327 measured $\text{NH}_4\text{-N}$ release rates when manure was applied below or between snow layers were
328 88.6, 45.7, and 24.0 mg (Table 3). Therefore, Eq. [3] reliably estimated manure $\text{NH}_4\text{-N}$ release
329 for these two manure placements. However, corresponding measured $\text{NH}_4\text{-N}$ release rates when
330 manure was applied on top of snow was 64.3, 30.7, and 15.9 mg (Table 3). Therefore, Eq. [3]
331 over-estimated manure $\text{NH}_4\text{-N}$ release for this manure placement. It is reasonable to assume that
332 overprediction is due to unaccounted for NH_3 volatilization from manure applied on top of snow.
333 In fact, if we assume a NH_3 volatilization rate of 35% for manure applied on top of snow, as
334 reported by Steenhuis et al. (1979) (i.e., 35% less manure $\text{NH}_4\text{-N}$ available to leach), predicted
335 $\text{NH}_4\text{-N}$ release in snowmelt would be 56.1, 29.0, and 14.8 mg, which is close to measured
336 values. Converse to P, these data also demonstrate that when estimating manure $\text{NH}_4\text{-N}$ release
337 from a semi-solid manure during snowmelt, incomplete snowmelt water interaction with manure
338 does not need to be considered. This may be because $\text{NH}_4\text{-N}$ release is much less sensitive to the
339 amount of water that interacts with manure (Fig. 2).

340 For the liquid manure, manure solids application rates and W values are in Table 4.
341 Applying Eq. [3] resulted in predicted $\text{NH}_4\text{-N}$ release amounts of 479.0, 239.5, and 112.7 mg for
342 the high, medium, and low application rates, respectively (Table 4). Corresponding measured
343 $\text{NH}_4\text{-N}$ release rates were clearly much less at 266.7, 150.1, and 79.5 mg (Table 3). If we
344 attribute overprediction to NH_3 volatilization from applied manure, a volatilization rate of 35%
345 of applied manure $\text{NH}_4\text{-N}$ would result in predicted $\text{NH}_4\text{-N}$ release during snowmelt of 282.2,
346 146.6, and 78.9 mg, which agreed well with measured rates. Overall, our data suggest that water
347 extraction data can be used to reliably estimate manure $\text{NH}_4\text{-N}$ release during snowmelt without
348 having to consider temperature or NH_3 volatilization if a semi-solid to solid manure is covered
349 by snow. However, NH_3 volatilization needs to be accounted for with liquid manures at all
350 placements in a snowpack and a semi-solid manure applied on top of snow.

351

352 **Conclusions**

353 Our lab-scale experiments suggest that temperature may not significantly influence
354 manure WEP and $\text{NH}_4\text{-N}$ release to water. Also, manure WEP release, but not $\text{NH}_4\text{-N}$ release, to
355 water will be influenced by the water-to-manure solids ratio. Manure placement within a
356 snowpack may not significantly influence snowmelt interaction with manure and leaching of
357 DRP. For semi-solid manures, the amount of $\text{NH}_4\text{-N}$ leached during snowmelt can increase with
358 the depth of snow covering it. This is mostly likely because manure applied on top of snow, and
359 even between snow layers, has greater NH_3 volatilization and thus less $\text{NH}_4\text{-N}$ available for
360 leaching loss. For liquid manures, NH_3 volatilization may not vary as a function of placement in
361 a snowpack, but liquid manures applied to snow will have greater NH_3 volatilization than more
362 solid manures unless the solid manures are applied on top of snow and have significant NH_3

363 volatilization. Finally, lab water extractions can be used to reliably estimate manure $\text{NH}_4\text{-N}$
364 release during snowmelt, but variations in NH_3 volatilization need to be accounted for with
365 liquid manures at all placements in a snowpack and a semi-solid manure applied on top of snow.
366 Lab water extractions can also be used to estimate DRP release from manure during snowmelt;
367 but for semi-solid to solid manures, the amount of snowmelt water that actually interacts with the
368 manure and subsequent WEP release is significantly less compared to water interaction with
369 manure during a rain event. The same is not true for liquid manures applied to snow. This may
370 be because liquid manure is more evenly distributed and absorbed into a snowpack than a semi-
371 solid manure, and thus has a greater potential for complete snowmelt interaction. This possibility
372 of more complete snowmelt interaction with liquid manures but incomplete snowmelt water
373 interaction with more solid manure during DRP release deserves further investigation, especially
374 as a function of a range of manure solids content. Overall, our data will help improve simulation
375 models that can be applied to explore the management and environmental implications of winter
376 manure spreading and variable winter runoff conditions.

377

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473 Figure Captions

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

479

480 Figure 2. Manure $\text{NH}_4\text{-N}$ release for the Arlington liquid dairy manure and the DFRC and MN
481 semi-solid dairy manures during water extraction experiments as a function of extraction
482 temperature and extraction ratio (water to manure solids, $\text{cm}^3 \text{g}^{-1}$). Bars indicate the standard
483 deviation of the means.

484

485 Figure 3. Change in dissolved P and $\text{NH}_4\text{-N}$ concentrations in snowmelt water with increasing
486 leachate volume during snowmelt leaching experiments with the Arlington liquid dairy manure
487 applied at three different rates. Data for a given rate are averaged across manure placements in
488 the snowpack. Bars indicate the standard deviation of the means.

489

490 Figure 4. Change in dissolved P and $\text{NH}_4\text{-N}$ concentrations in snowmelt water with increasing
491 leachate volume during snowmelt leaching experiments with the DFRC semi-solid dairy manure
492 applied at three different rates. Data for a given rate are averaged across manure placements in
493 the snowpack. Bars indicate the standard deviation of the means.

494

495 Table 1. ANOVA for effects of manure, extraction ratio, and temperature on manure WEP and NH₄-N extracted during water496 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

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505 Table 2. ANOVA for effects of manure, extraction ratio, and temperature on manure DRP and NH₄-N leached during snowmelt

506 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

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513 Table 3. Cumulative manure DRP and NH₄-N release (mg) for the Arlington Liquid and DFRC semi-solid dairy manures during
 514 snowmelt experiments as a function of manure application rate (Low, Medium, High) and manure placement within a snowpack
 515 (under snow, between snow layers, and on top of snow). Values in parentheses are DRP and NH₄-N release expressed as percentages
 516 of total P and total N applied as manure.

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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)

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522 Table 4. Data for manure solids applied, water:solids ratio, manure total P and N applied, and predicted DRP and NH₄-N release for

523 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

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¹ Dry weight equivalent

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

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

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⁴ Predictions use Eq. [3]

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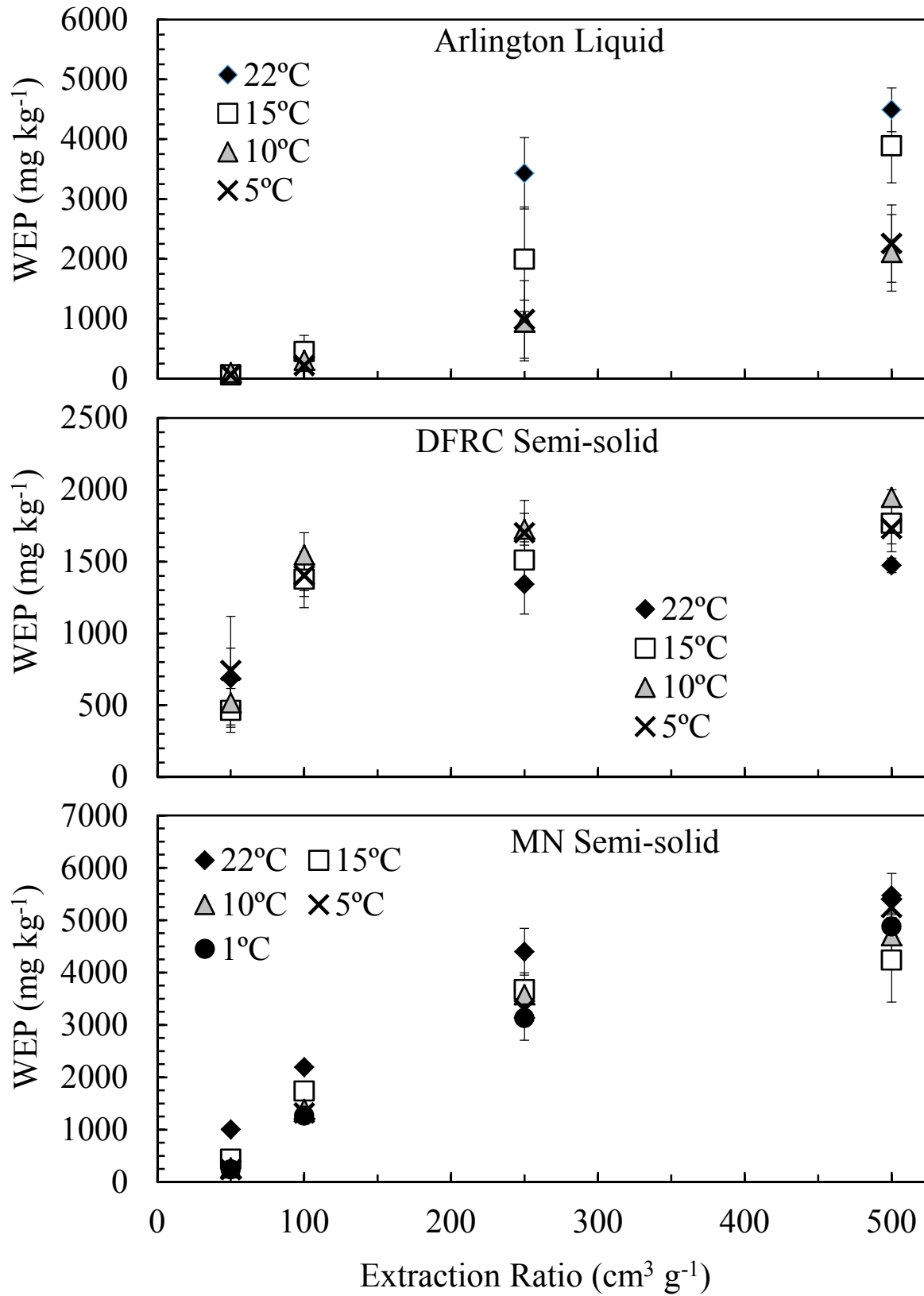


Figure 2.

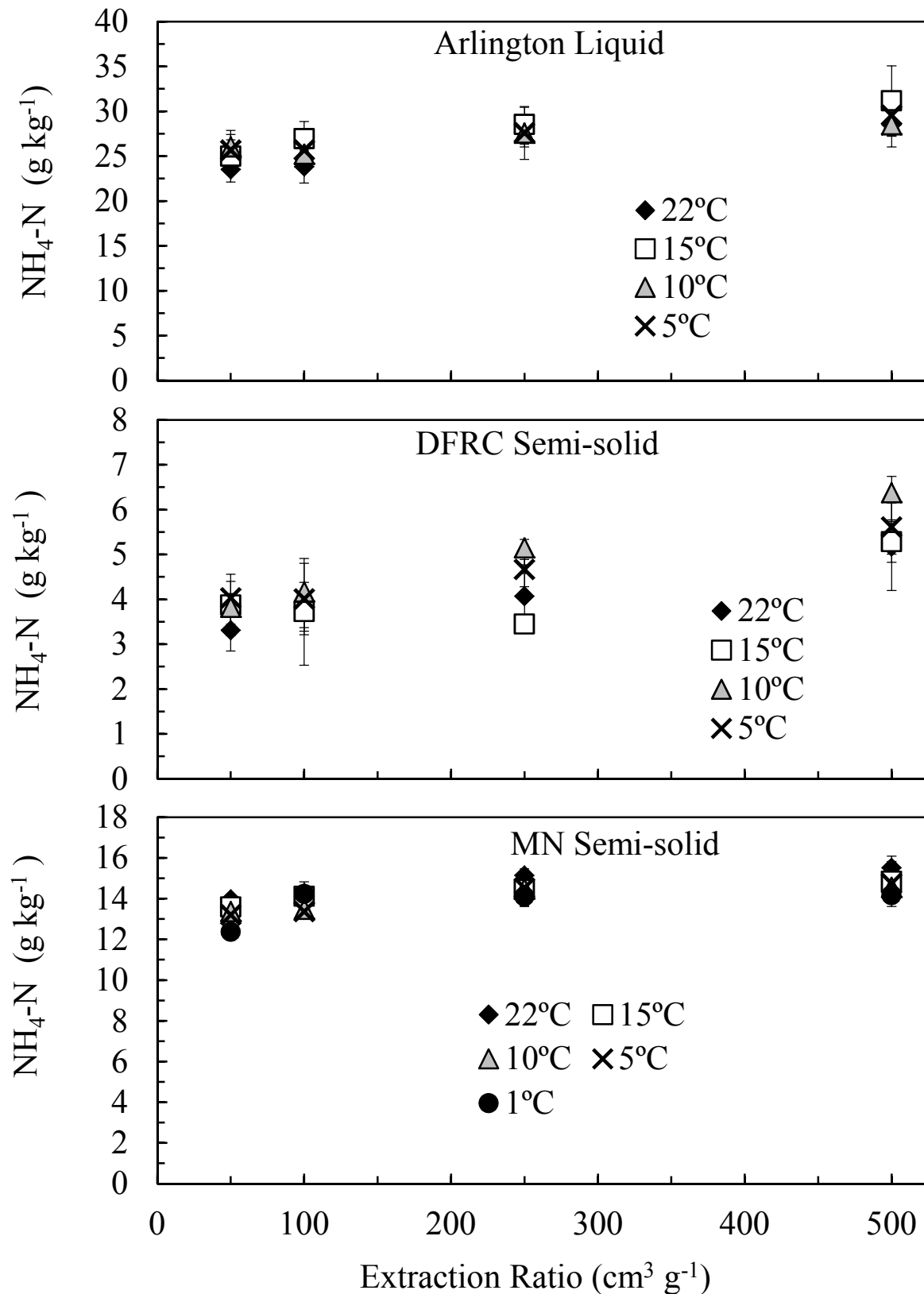


Figure 3

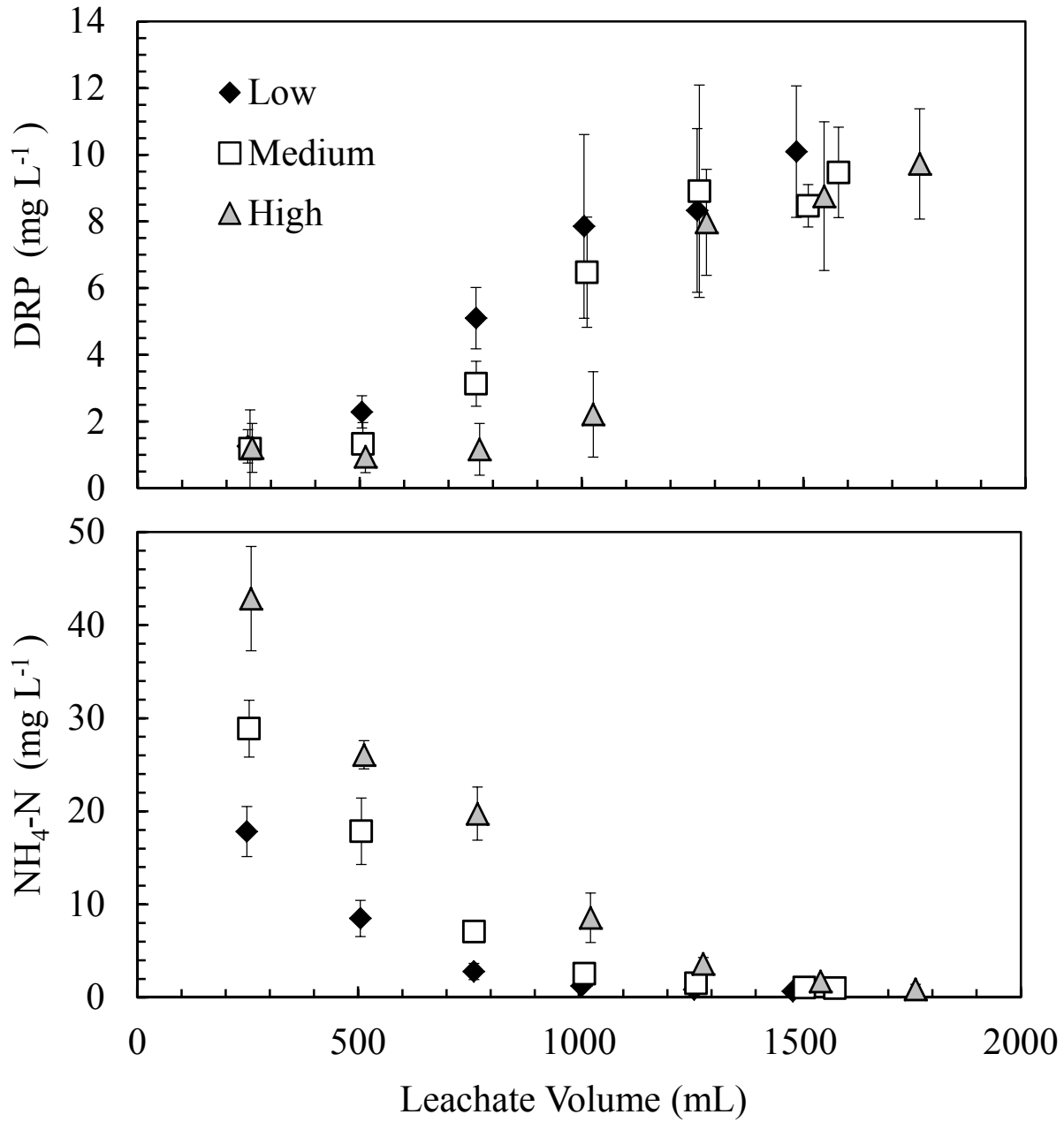
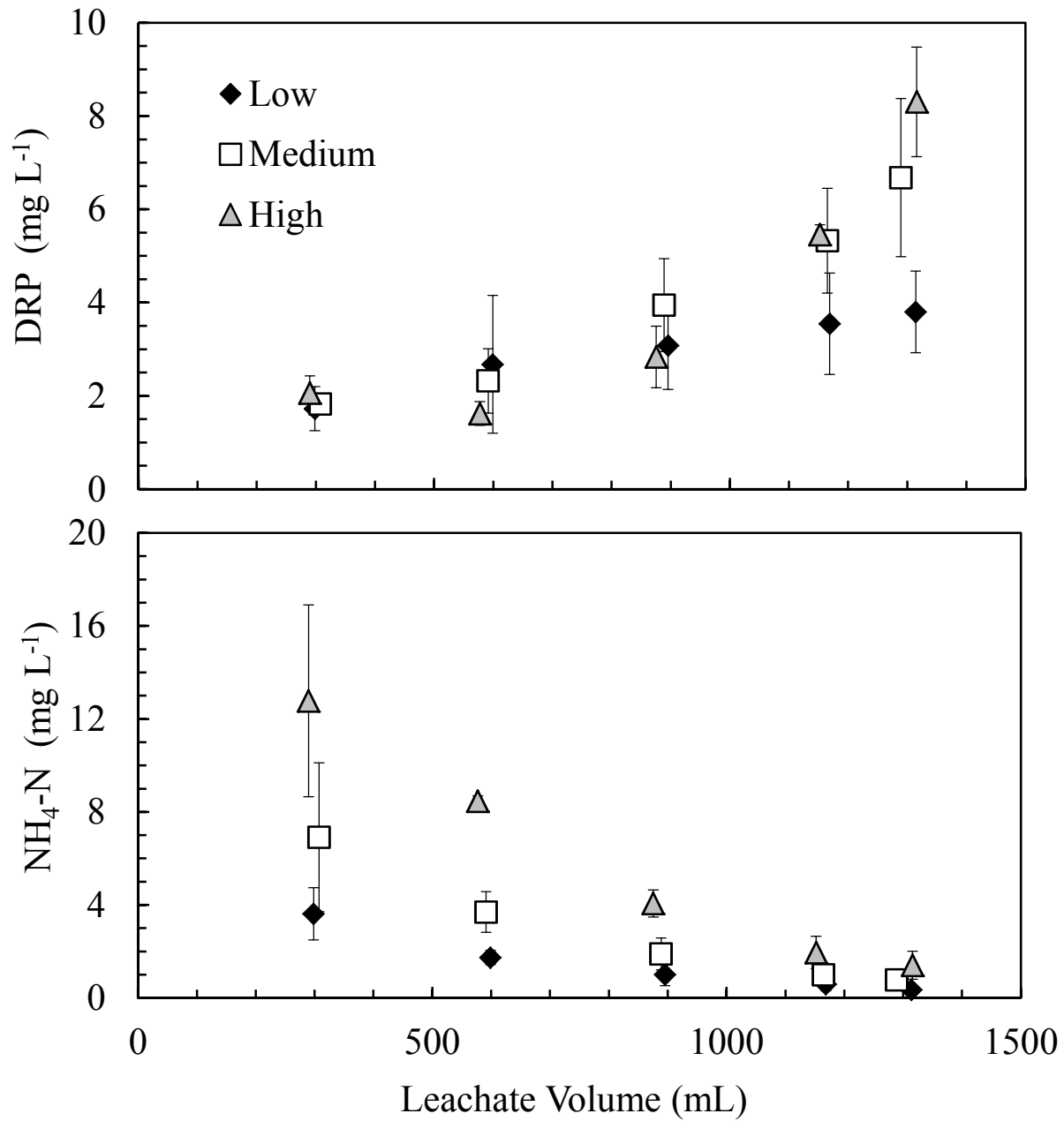


Figure 4

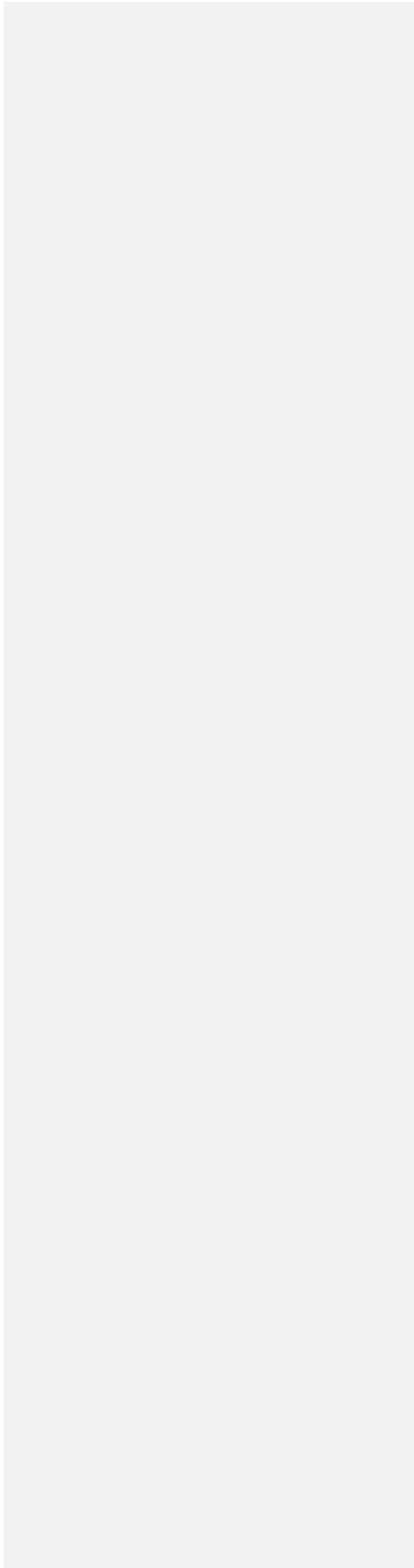


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**Temperature and Manure Placement in a Snowpack Affect
Nutrient Release from Dairy Manure during Snowmelt**

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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.

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

64 The potential for manure nutrient runoff during winter is complex and can vary due to
65 infiltration, runoff, erosion, and nutrient cycling processes, all of which are sensitive to air
66 temperatures and frozen soil conditions. Nutrient loss may also vary with manure spreading
67 practices, especially relative to manure placement beneath or on top of snow and the effect of
68 manure on rates of snow melt (Kongoli and Bland, 2002). Detailed studies of soil and manure
69 | interactions and the hydrological processes that affect nutrient transport under winter conditions

70 | are limited. Most studies have been observational with mixed results regarding the degree to
71 | which winter manure application increases the risk of nutrient runoff relative to manure
72 | application in other seasons.— A majority of research was conducted before 1980 (Converse et
73 | al., 1976; Steenhuis et al., 1981; Young and Mutchler, 1976; Young and Holt, 1977; Klausner et
74 | al., 1976; Phillips et al., 1981). While there has been some more recent research (Hansen et al.,
75 | 2000; Komiskey et al., 2011; Lewis and Makarewicz, 2009; Owens et al., 2011; Ulen, 2003), it
76 | was observational at the field-scale or larger, and did not provide data on liquid manures. The
77 | review paper of Srinivasan et al. (2006) details the results of most of these studies. Only the
78 | recent research of Williams et al. (2011; 2012b, a) has investigated winter processes at the
79 | controlled lab scale. Overall, a process-level understanding of nutrient cycling and transport
80 | processes associated with winter manure application is lacking, especially for liquid manures.

81 | Our ~~major research~~ goal is to ~~investigate and~~ improve the understanding and modeling of
82 | biochemical and physical processes controlling frozen-soil and snowmelt infiltration, runoff, and
83 | nutrient loss from soil and winter-applied dairy manure. ~~We are addressing this goal~~ through a
84 | series of lab and field-plot scale experiments. Lab experiments, such as the ones reported here,
85 | ~~are designed to~~ investigate specific processes under controlled conditions at small scales rather
86 | than under variable weather at field scales, which combined can make it difficult to identify
87 | relative importance of multiple processes. The specific objectives in the current lab experiments
88 | were to 1) investigate if less P and NH₄ are released from manure to water due to low
89 | temperatures that would occur during snowmelt (as compared to rain events in non-winter
90 | periods); 2) investigate the effect of dairy manure solids content, application amount, and
91 | placement within a snowpack on P and NH₄ release to melting snow; and 3) determine if

92 relationships from Objective 1 can reliably predict nutrient release from manure during snowmelt
93 in Objective 2.

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96 **Materials and Methods**

97 **Manure Extraction Experiments at Different Temperatures**

98 We collected three dairy manures from Holstein lactating cows: i) a liquid manure at the
99 University of Wisconsin cattle research center in Arlington, WI (Arlington liquid); ii) a semi-
100 solid manure at the USDA Dairy Forage Research Center (DFRC semi-solid) farm in Prairie du
101 Sac, WI; and iii) a semi-solid manure from a commercial farm in Minnesota (MN manure). The
102 Arlington liquid manure was from a storage lagoon and had a solids content of 4.6% as
103 determined gravimetrically after drying at 65°C. Manure in the lagoon was from a barn flush
104 system where bedding sand had been separated by gravity settling. On a dry-weight basis, total N
105 content was 77.6 g kg⁻¹, and total P content was 11.0 g kg⁻¹. The DFRC (12.6% solids) and MN
106 (11.6% solids) semi-solid manures were both collected from the floor of free-stall barns at the
107 point of mechanical consolidation. For the DFRC manure, dry-weight-basis total N content was
108 28.0 g kg⁻¹, and total P content was 5.3 g kg⁻¹. For the MN manure, dry-weight-basis total N
109 content was 43.8 g kg⁻¹, and total P content was 9.0% g kg⁻¹. Manures were stored at 4°C when
110 not in use.

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

115 Kleinman (2006) where fresh manure was shaken with deionized water for 1 h at different
116 extraction ratios ($\text{cm}^3 \text{g}^{-1}$, dry weight equivalent). Our extraction ratios included 50:1, 100:1,
117 250:1, and 500:1, and temperatures included 22, 15, 10, and 5°C. The MN manure was also
118 extracted at 1°C. For extractions, we weighed manure and water into separate flasks, placed them
119 into a temperature-controlled shaker and let them equilibrate to the desired temperature for at
120 least 24 h without shaking. We then combined the water and manure, shook the mixtures for 1 h,
121 and filtered them through 0.45 μm filters. We analyzed the filtered samples for dissolved reactive
122 P (DRP) colorimetrically (Murphy and Riley, 1962) on a spectrophotometer, and for $\text{NH}_4\text{-N}$ and
123 $\text{NO}_3\text{-N}$ on a Lachat automated analyzer (Hach Company, Loveland, CO) using QuickChem
124 Methods 12-107-06-2-A (ammonium) and 12-107-04-1-B (nitrate). Throughout the experiments,
125 $\text{NO}_3\text{-N}$ concentrations in manure extractions and snowmelt leachings (see below) were
126 negligible, so we do not present data for this N form.

127

128 **Snowmelt Leaching Experiments**

129 | We designed these experiments to investigate nutrients release from manure to melting
130 snow water. This is the first step in understanding and modeling potential manure nutrient
131 transport in runoff. We therefore conducted experiments with snow and manure only, in the
132 absence of underlying soil. We used only the Arlington liquid manure and DFRC semi-solid
133 manure for these leaching experiments. We conducted experiments in triplicate using 15-cm
134 diameter funnels that had flat bottoms and a series of small drainage holes. We collected natural
135 snow and stored it frozen until use. We added snow and manure to funnels to achieve three rates
136 of manure, and three manure placements in a snowpack, which were below snow, between two
137 equivalent snow layers, and on top of snow. For the liquid manure, we added a snow equivalent

138 of 1400 mL of water and manure at three wet-weight amounts of 98, 197 and 394 g. This
139 achieved a relatively wide range of liquid (including snow and manure liquid) to manure dry
140 matter ratios of 96, 174, and 331 cm³ g⁻¹ (Table 4). For the semi-solid manure, we added a snow
141 equivalent of 1250 mL of water and manure at wet-weight rates of 32, 68 and 136 g. This
142 achieved liquid to manure dry matter ratios of 74, 144, and 315 cm³ g⁻¹ (Table 4). For each
143 funnel, we froze a piece of acid-washed, nylon screen in 30 mL of deionized water and placed
144 the screen in the funnel before adding any manure or snow. This prevented any immediate loss
145 of manure through funnels before snowmelt began. When assembled, we placed all funnels in a
146 cold room ~~of about~~ at approximately 4°C and allowed snow to melt, which took between 44 to 58
147 h. During melt, we collected all leachate in increments of ~~every~~ 250-300 mL. We filtered and
148 analyzed all samples for NH₄ and P as described above.

149

150 **Statistical Analysis**

151 We used the general linear model of SAS (SAS Version 9.4) along with Tukey's mean
152 separation to conducted a statistical analysis of results. For the water extraction experiment,
153 variables of DRP and NH₄-N, total treatment sums of squares (SS) for the fixed effects in the
154 ANOVA were partitioned into partial SS associated with the three manure types, four extraction
155 ratios, five temperatures, and all their two-way and three-way treatment interactions. We used
156 partial SS to determine the percentage of total DRP and NH₄-N associated with each treatment
157 effect or treatment interaction. Treatment differences discussed in the text were significant at the
158 0.05 probability level. We conducted a similar statistical analysis for the funnel leaching
159 experiments, where fixed effects were the two manure types, three application rates, three
160 placements in the snowpack, and all their two-way and three-way treatment interactions.

161

162 Results and Discussion**163 Manure Extraction Experiments**

164 Throughout the discussion, we refer to DRP analyzed in manure extractions as water
165 extractable P (WEP) to be consistent with terminology in previous studies on manure P
166 extractability (Kleinman et al., 2002; Vadas and Kleinman, 2006; Kleinman et al., 2005). Figure
167 1 shows results for manure WEP (mg kg^{-1} dry weight equivalent) for the three dairy manures as a
168 function of extraction ratio and temperature. Statistical analysis indicated that only extraction
169 ratio had a significant effect on WEP, and explained 60% of its variability (Table 1). This was
170 true for WEP expressed on a mass basis (mg kg^{-1} dry weight equivalent) or as a percent of total P
171 in the manure. Manure type and the manure by extraction ratio interaction each explained 16% of
172 WEP variability, but were not statistically significant. Across all three manures, temperature did
173 not significantly affect WEP, even though there was less WEP from the Arlington liquid manure
174 as temperature decreased from 22°C to 10°C, with no further decrease less than 10°C. This
175 suggests cold temperatures do not affect P release from manure substantially enough that models
176 need to account for the variable (Bechmann et al., 2005).

177 Figure 2 shows results for water extractable manure $\text{NH}_4\text{-N}$ as a function of extraction
178 ratio and temperature. Statistical analysis showed that only manure type had a significant effect
179 on extractable $\text{NH}_4\text{-N}$, and explained 98% of the data variability (Table 1). There was greater
180 extractable $\text{NH}_4\text{-N}$ for the liquid manure than the semi-solid manures, which did not differ from
181 each other. While this statistical effect of manure type was true on a mass basis (mg kg^{-1} dry
182 weight equivalent), it was not true for $\text{NH}_4\text{-N}$ expressed as a percent of total N in manure. Since
183 total N content varied from 28.0 to 77.6 g kg^{-1} across manures, comparing data as a percent of

184 total N may be more equitable. Given that, Figure 2 shows that manure $\text{NH}_4\text{-N}$ release to water
185 was fairly rapid and complete regardless of temperature, extraction ratio, or manure type. Good
186 (2002) also observed no effect of extraction ratio on manure $\text{NH}_4\text{-N}$ release. This suggests that
187 models do not need to account for these variables when estimating $\text{NH}_4\text{-N}$ release from manure
188 during snowmelt.

189

190 **Phosphorus Dynamics during Snowmelt Leaching**

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

198 Table 3 presents cumulative manure DRP released (mg) for both the liquid and semi-
199 solid manures over the entire snowmelt period. Statistical analysis in Table 2 shows that on a
200 mass basis (mg) there was no effect of manure type, placement in the snowpack, or application
201 rate on cumulative DRP released. However, when expressed as a percent of total manure P
202 applied, there was an effect of application rate on cumulative DRP released (Table 2). ~~This~~
203 ~~means that~~ Thus, the proportion of applied manure total P that leached decreased as application
204 rate increased. The three manure application rates during snowmelt represented about 50, 100,
205 and 200 mg applied total P for the liquid manure and 21, 45, and 91 mg for the DFRC semi-solid
206 manure for the high, medium, and low application rates, respectively (Table 4). Therefore, the

207 amount of manure DRP leached during snowmelt was about 5, 9, and 17% of total P applied for
208 the high, medium, and low application rates for both manures. These results are consistent with
209 our lab extraction data showing that P leaching is a function of the water:solids extraction ratio
210 and that a greater percentage of manure P is released at greater ratios (Vadas et al., 2004; Vadas
211 et al., 2005). In the snowmelt leaching experiments, as the amount of applied manure increased,
212 the ratio of snow water to manure solids (equivalent to extraction ratio during the water
213 extraction experiments) decreased, and thus the percentage of applied P that was released also
214 decreased.

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

230 suggests nutrient runoff models do not need to account for manure placement in a snowpack for
231 P.

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

235

$$236 \text{ DRP release} = [1.2W/(W + 73.1)](\text{manure WEP}) \quad [1]$$

237

238 where W is the water to manure extraction ratio ($\text{cm}^3 \text{g}^{-1}$), WEP is the manure DRP that is
239 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
240 the same units as WEP. Equation [1] fit well to the lab extraction data for the DFRC semi-solid
241 manure in Figure 1 ($r^2 = 0.70$), so we applied Eq. [1] to see if it could reliably estimate DRP
242 release from manure during our snowmelt leaching experiments. For the semi-solid manure,
243 manure solids application rates and W values during snowmelt leaching are in Table 4. We
244 estimated a manure WEP of 1560 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1.
245 Applying Eq. [1] resulted in estimated DRP release amounts of 16.1, 10.6, and 6.1 mg for the
246 high, medium, and low application rates, respectively (Table 4). Corresponding measured rates
247 as averaged across manure placements in snow were 4.7, 4.5, and 3.7 mg for high, medium, and
248 low application rates (Table 3).

249 Clearly, less DRP was leached from the semi-solid manure during snowmelt than Eq. [1]
250 would estimate. If we assume that the basic leaching processes represented by Eq. [1] still
251 applied, underestimated DRP leaching suggests that not all the snowmelt water interacted with
252 manure and that W as applied in Eq. [1] should have been less. In fact, the degree to which

253 measured DRP release was less than that estimated by Eq. [1] was consistent. We calculated that
254 if only 20% of snowmelt water actually interacted with manure, then Eq. [1] W values would be
255 15, 29, and 63 cm³ g⁻¹; and corresponding estimated DRP release would be 4.7, 4.5, and 3.5 mg,
256 for the high, medium, and low application rates, respectively. These estimated DRP release
257 values are similar to measured values (Table 3).

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

268 For the Arlington liquid manure, Eq. [1] did not effectively describe the lab WEP
269 extraction data in Figure 1 ($r^2 = 0.05$). The reason for this is unknown, but could be related to
270 manure P mineralogy, which can be a function of animal diet or bedding material (Pagliari,
271 2011). The liquid manure WEP extraction data instead exhibited a linear increase in manure
272 WEP with W, while Eq. [1] is nonlinear. Therefore, we used data from Figure 1 (as averaged
273 across all temperatures) to represent DRP release from the liquid manure as:

274

$$275 \text{ DRP release} = (0.005 W - 0.253)(\text{manure WEP}) \quad r^2=0.96 \quad [2]$$

276
277 For the liquid manure, manure solids application amounts and W values are in Table 4. We
278 estimated a manure WEP of 1840 mg kg^{-1} based on data at the 250:1 extraction ratio in Figure 1.
279 Applying Eq. [2] resulted in manure DRP release amounts of 8.4, 10.3 and 7.7 mg for the high,
280 medium, and low application rates, respectively (Table 4). Corresponding measured rates were
281 7.8, 8.0, and 8.6 mg for the high, medium, and low application rates (Table 3). Similar to the
282 DFRC semi-solid manure, these liquid manure results suggest that lab water extraction data can
283 be used to estimate DRP release from manure during snowmelt, without considering temperature
284 or manure placement in a snowpack during snowmelt. Data also demonstrate that when
285 estimating DRP release from a liquid manure during snowmelt, incomplete snowmelt water
286 interaction with manure does not need to be considered. This may be because liquid manure is
287 more evenly distributed and absorbed into the snowpack than a semi-solid manure, and thus has
288 a potential for greater snowmelt interaction. As before, this possibility of more complete
289 snowmelt interaction with liquid manure but incomplete snowmelt water interaction with more
290 solid manure deserves further investigation.

291

292 **Nitrogen Dynamics during Snowmelt Leaching**

293 In all leaching experiments, $\text{NH}_4\text{-N}$ concentrations in snow water without manure were
294 less than 0.30 mg L^{-1} . Results in Figures 3 and 4 show that $\text{NH}_4\text{-N}$ concentrations in incremental
295 leachate water from both the liquid and semi-solid manures decreased as snowmelt progressed.
296 These data are consistent with our lab extractions that showed $\text{NH}_4\text{-N}$ release is not a function of
297 how much water interacts with manure. Thus during snowmelt, $\text{NH}_4\text{-N}$ release would be
298 expected to be rapid even with only low amounts of snowmelt water (first flush phenomenon).

299 Statistical analysis in Table 2 shows that only manure type had a significant effect on
300 mass (mg) of cumulative $\text{NH}_4\text{-N}$ leached during snowmelt (Table 3). However, when $\text{NH}_4\text{-N}$
301 release was expressed as a function of total N applied in manure, no treatment variables had a
302 significant effect on $\text{NH}_4\text{-N}$ leached (Table 2). ~~This means that~~ Thus, a similar percentage of
303 applied total N leached from manure regardless of application rate and thus snow water:manure
304 solids ratio. For both manures, an average of 19.2% (s.d. of 2.3%) of applied manure total N was
305 leached.

306 For the semi-solid manure, although placement in the snowpack was not a significant
307 factor (Table 2), the amount of $\text{NH}_4\text{-N}$ leached during snowmelt consistently increased with the
308 depth of snow covering it (Table 3). This is most likely because manure applied on top of snow,
309 and even between snow layers, had longer direct exposure to the air above it, had greater NH_3
310 volatilization, and thus had less $\text{NH}_4\text{-N}$ available for leaching loss (Williams et al., 2011; Lauer
311 et al., 1976). Steenhuis et al. (1979) observed about 35% greater NH_3 volatilization from a dairy
312 manure (16% solids) placed on top of a snow pack compared to below a 10cm snowpack over
313 four days. Similarly, we observed about 30% more $\text{NH}_4\text{-N}$ in leachate from our semi-solid
314 manure when manure was below the snowpack compared to on top. An average of 20.6% (s.d. of
315 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
316 $\text{NH}_4\text{-N}$ for the manure below, in between, and on top of snow, respectively. For the liquid
317 manure at a given manure application rate, there was no trend of manure placement within the
318 snowpack on $\text{NH}_4\text{-N}$ leached during snowmelt (Table 3). An average of 20.9% (s.d. of 2.3%) of
319 manure total N was leached as $\text{NH}_4\text{-N}$. Therefore, our data suggest that NH_3 volatilization may
320 not vary as a function of placement in a snowpack for liquid manure.

321 Similar to P, we investigated if our water extraction data could reliably estimate NH₄-N
322 release from manure during snowmelt. Combining the data from all three manures in Figure 2,
323 we developed the equation below (similar to Eqs. [1] and [2]):

324

$$325 \text{ NH}_4 \text{ release} = (0.0004 W - 0.758)(\text{manure NH}_4\text{-N}) \quad r^2=0.50 \quad [3]$$

326

327 Solids application rates and W values during snowmelt leaching are in Table 4. We estimated
328 manure NH₄-N from maximum amounts extracted during water extractions (Figure 2). Applying
329 Eq. [3] for the semi-solid manure resulted in predicted NH₄-N release of 86.3, 44.7, and 22.8 mg
330 for the high, medium, and low application rates, respectively (Table 4). Corresponding average
331 measured NH₄-N release rates when manure was applied below or between snow layers were
332 88.6, 45.7, and 24.0 mg (Table 3). Therefore, Eq. [3] reliably estimated manure NH₄-N release
333 for these two manure placements. However, corresponding measured NH₄-N release rates when
334 manure was applied on top of snow was 64.3, 30.7, and 15.9 mg (Table 3). Therefore, Eq. [3]
335 over-estimated manure NH₄-N release for this manure placement. It is reasonable to assume that
336 overprediction is due to unaccounted for NH₃ volatilization from manure applied on top of snow.
337 In fact, if we assume a NH₃ volatilization rate of 35% for manure applied on top of snow, as
338 reported by Steenhuis et al. (1979) (i.e., 35% less manure NH₄-N available to leach), predicted
339 NH₄-N release in snowmelt would be 56.1, 29.0, and 14.8 mg, which is close to measured
340 values. Converse to P, these data also demonstrate that when estimating manure NH₄-N release
341 from a semi-solid manure during snowmelt, incomplete snowmelt water interaction with manure
342 does not need to be considered. This may be because NH₄-N release is much less sensitive to the
343 amount of water that interacts with manure (Fig. 2).

344 For the liquid manure, manure solids application rates and W values are in Table 4.
345 Applying Eq. [3] resulted in predicted $\text{NH}_4\text{-N}$ release amounts of 479.0, 239.5, and 112.7 mg for
346 the high, medium, and low application rates, respectively (Table 4). Corresponding measured
347 $\text{NH}_4\text{-N}$ release rates were clearly much less at 266.7, 150.1, and 79.5 mg (Table 3). If we
348 attribute overprediction to NH_3 volatilization from applied manure, a volatilization rate of 35%
349 of applied manure $\text{NH}_4\text{-N}$ would result in predicted $\text{NH}_4\text{-N}$ release during snowmelt of 282.2,
350 146.6, and 78.9 mg, which agreed well with measured rates. Overall, our data suggest that water
351 extraction data can be used to reliably estimate manure $\text{NH}_4\text{-N}$ release during snowmelt without
352 having to consider temperature or NH_3 volatilization if a semi-solid to solid manure is covered
353 by snow. However, NH_3 volatilization needs to be accounted for with liquid manures at all
354 placements in a snowpack and a semi-solid manure applied on top of snow.

355

356 **Conclusions**

357 Our lab-scale experiments suggest that temperature may not significantly influence
358 manure WEP and $\text{NH}_4\text{-N}$ release to water. Also, manure WEP release, but not $\text{NH}_4\text{-N}$ release, to
359 water will be influenced by the water-to-manure solids ratio. Manure placement within a
360 snowpack may not significantly influence snowmelt interaction with manure and leaching of
361 DRP. For semi-solid manures, the amount of $\text{NH}_4\text{-N}$ leached during snowmelt can increase with
362 the depth of snow covering it. This is mostly likely because manure applied on top of snow, and
363 even between snow layers, has greater NH_3 volatilization and thus less $\text{NH}_4\text{-N}$ available for
364 leaching loss. For liquid manures, NH_3 volatilization may not vary as a function of placement in
365 a snowpack, but liquid manures applied to snow will have greater NH_3 volatilization than more
366 solid manures unless the solid manures are applied on top of snow and have significant NH_3

367 volatilization. Finally, lab water extractions can be used to reliably estimate manure $\text{NH}_4\text{-N}$
368 release during snowmelt, but variations in NH_3 volatilization need to be accounted for with
369 liquid manures at all placements in a snowpack and a semi-solid manure applied on top of snow.
370 Lab water extractions can also be used to estimate DRP release from manure during snowmelt;
371 but for semi-solid to solid manures, the amount of snowmelt water that actually interacts with the
372 manure and subsequent WEP release is significantly less compared to water interaction with
373 manure during a rain event. The same is not true for liquid manures applied to snow. This may
374 be because liquid manure is more evenly distributed and absorbed into a snowpack than a semi-
375 solid manure, and thus has a greater potential for complete snowmelt interaction. This possibility
376 of more complete snowmelt interaction with liquid manures but incomplete snowmelt water
377 interaction with more solid manure during DRP release deserves further investigation, especially
378 as a function of a range of manure solids content. Overall, our data will help improve simulation
379 models that can be applied to explore the management and environmental implications of winter
380 manure spreading and variable winter runoff conditions.

381

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483 Figure Captions

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485 Figure 1. Manure WEP release for the Arlington liquid dairy manure and the DFRC and MN

486 semi-solid dairy manures during water extraction experiments as a function of extraction

487 temperature and extraction ratio (water to manure solids, $\text{cm}^3 \text{g}^{-1}$). ~~Letters~~ Bars indicate a488 ~~significant effect of temperature ($p=0.05$) at that specific extraction ratio only~~ the standard489 deviation of the means.

490

491 Figure 2. Manure $\text{NH}_4\text{-N}$ release for the Arlington liquid dairy manure and the DFRC and MN

492 semi-solid dairy manures during water extraction experiments as a function of extraction

493 temperature and extraction ratio (water to manure solids, $\text{cm}^3 \text{g}^{-1}$). Bars indicate the standard494 deviation of the means.495 ~~Letters indicate a significant effect of temperature ($p=0.05$) at that specific extraction ratio only.~~

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497 Figure 3. Change in dissolved P and NH₄-N concentrations in snowmelt water with increasing
498 leachate volume during snowmelt leaching experiments with the Arlington liquid dairy manure
499 applied at three different rates. Data for a given rate are averaged across manure placements in
500 the snowpack. Bars indicate the standard deviation of the means.

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503 Figure 4. Change in dissolved P and NH₄-N concentrations in snowmelt water with increasing
504 leachate volume during snowmelt leaching experiments with the DFRC semi-solid dairy manure
505 applied at three different rates. Data for a given rate are averaged across manure placements in
506 the snowpack. Bars indicate the standard deviation of the means.

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509 Table 1. ANOVA for effects of manure, extraction ratio, and temperature on manure WEP and NH₄-N extracted during water
 510 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

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519 Table 2. ANOVA for effects of manure, extraction ratio, and temperature on manure DRP and NH₄-N leached during snowmelt

520 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	Df	DRP		Percent of Total P		NH ₄ -N		Percent of Total N	
		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

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527 Table 3. Cumulative Manure DRP and NH₄-N release (mg) for the Arlington Liquid and DFRC semi-solid dairy manures during
 528 snowmelt experiments as a function of manure application rate (Low, Medium, High) and manure placement within a snowpack
 529 (under snow, between snow layers, and on top of snow). Values in parentheses are DRP and NH₄-N release expressed as percentages
 530 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

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536 Table 4. Data for manure solids applied, water:solids ratio, manure total P and N applied, and predicted DRP and NH₄-N release for
 537 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

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¹Dry weight equivalent

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

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

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⁴Predictions use Eq. [3]

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