SOIL HEALTH NEXUS

Winter Manure Application: Management Practices and Environmental Impact

2016 Manure and Soil Health Working Group Report

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1. Background

The practice of manure application on frozen or snowy soils remains controversial. References show that such application to frozen impermeable soils can increase the risk of manure nutrients and contaminants running off of fields during the spring thaw. Additionally, the loss of nutrients to spring thaws means a loss of soil productivity in addition to potentially impacting local water bodies (Thompson et al., 1979). As such, organizations such as the US Environmental Protection Agency (EPA) and the Natural Resource Conservation Service (NRCS) have traditionally discouraged manure application during winter (NRCS, 2013). However, winter manure application has several key benefits to farmers (Fleming and Fraser, 2000):

- Reducing the size and number of manure storage structures.
- Spreading the manure when logistics suite the farmer.
- Reducing soil compaction by avoiding equipment use during compressible soil conditions.

Winter manure application allows farmers to optimize workload efficiency by making use of a season that traditionally has fewer activities and keeps capital costs low by reducing the infrastructure needed to store manure. A 2016 survey conducted in Michigan found that a total ban on winter application would collectively cost small farms in the state an estimated $30 million dollars a year (Miller et al., 2017). Despite these benefits to producers, there is little doubt that winter spreading of manure comes with an elevated risk of nutrient loss to the environment, with several field, laboratory and modeling efforts demonstrating this risk (Srinivasan et al., 2006). Coupled with the emergence of environmental issues downstream of livestock operations such as algae blooms and fish kills, many states have chosen to ban winter manure application all together. However, banning winter manure application outright may come with certain disadvantages as well. Overtaxing long-term storage systems can lead to overflows, spills, or the need to make emergency applications during the spring thaw months, which are most sensitive to manure application (Komiskey et al., 2011). This sensitivity to manure releases can correspond with environmental sensitivities as well. Critically, the National Oceanic and Atmospheric Administration (NOAA) recently forecasted harmful algal blooms (HABs) in the Western Lake Erie basin using total phosphorus influent data for spring as it was found to be the most correlated anthropogenic factor (Stumpf et al., 2012). Figure 1 shows the NOAA spring total phosphorus and bloom density predictions from satellite data (Wynne et al., 2010). The importance of season specific nutrient releases on HAB formation gives new weight to the need to avoid heavy spring releases from manure application.

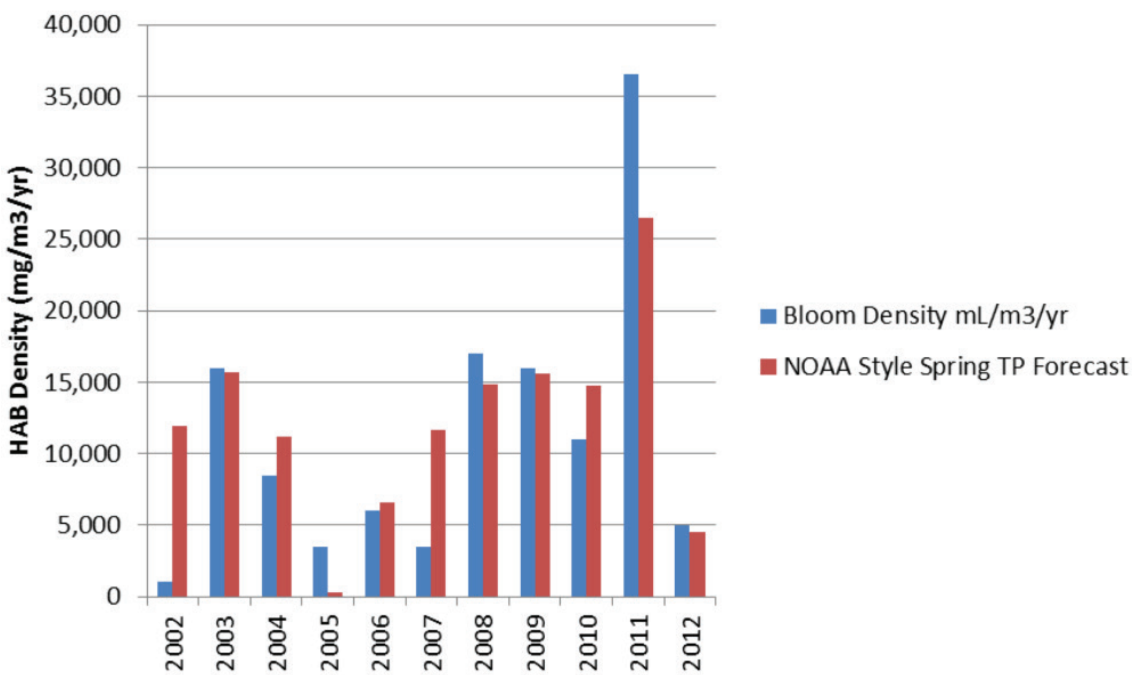

Figure 1: *Lake Erie Bloom Density and Predicted Bloom Density Using NOAA Spring TP Forecasting Model Derived from (Wynne et al., 2010)*

Winter manure application, at its core, is a risk management decision. The potential danger of nutrient releases needs to be weighed against the danger of large point source manure releases, as well as the economic hardships placed upon agricultural producers. The purpose of this literature review is to examine the state-of–the-literature on winter manure application with regard to existing contaminants of concern, case studies, existing best management practices, state level policy, and the efficacy of present management systems. The resulting analysis will identify data gaps, building upon the lessons learned in previous literature reviews (Fleming and Fraser, 2000; Srinivasan et al., 2006).

2. Contaminants of Concern

Manure runoff carries a number of contaminants that can cause health impact to water bodies and decrease aesthetics. Table 1 lists some of the most common contaminants contained in manure, the pathways to the environment, and the potential impacts. The sequential paragraphs discuss each in more detail.

Pollutant	Pathways to the Environment	Potential Negative Impacts
Nitrogen	• Overland discharge • Leachate into ground water • Atmospheric deposition as ammonia	• Eutrophication and HABs • Ammonia toxicity to aquatic life • Nitrate linked to methemoglobinemia
Phosphorus	• Overland discharge • Leachate into ground water (water soluble forms)	Eutrophication and harmful algae blooms
Potassium	• Overland discharge • Leachate into ground water	Increase salinity in surface water and ground water
Organic Compounds	• Overland discharge	• Eutrophication and HABs • Dissolved oxygen depletion and potentially anoxic
Pathogens	• Overland discharge • Potential growth in receiving waters	Animal, human health effects
Antimicrobials	• Overland discharge • Leachate into ground water • Atmospheric deposition	• Facilitates the growth of antimicrobial-resistance • Unknown human health and aquatic life effects

Table 1: *Manure Contaminants (Adapted from USEPA, 2013)*

2.1 Nutrients

Runoff from winter-applied manure can be an important source of annual nutrient loadings to water bodies, with nitrogen and phosphorous being the most often reported contaminants of concern. In a 1985 study, Moore and Madison estimated that 25% of annual phosphorus load to a Wisconsin lake was directly attributable to winter spread animal wastes (Moore and Madison, 1985). Brown et al. (1989) investigated the Cannonsville Reservoir in New York and determined that snowmelt runoff from winter manured cropland contributed more phosphorus to the reservoir than runoff from barnyards. Clausen and Meals (1989) estimated that 40% of Vermont's streams and lakes experienced significant water quality impairments from the addition of just two winter-spread fields in their watersheds.

Plot studies of winter-applied manure found that 23.5 to 1,086 mg/L of total Kjeldahl nitrogen (TKN) and 1.6 to 15.4 mg/L of phosphorus in runoff (Lorimor and Melvin, 1996; Thompson et al., 1979). In two Vermont field studies, Clausen (1990; 1991) reported 165 to 224% increases in total phosphorus concentration, 246 to 1,480% increases in soluble phosphorous, 114% increases in TKN, and up to a 576% increase in NH3-N following winter application of dairy manure. Mass losses of nutrient are highly variable across studies. Several studies have noted elevated though moderate mass losses of nitrogen ranging from 10-22% of applied nitrogen (Converse et al., 1976; Hensler et al., 1970; Klausner et al., 1976; Lorimor and Melvin, 1996; Midgley and Dunklee, 1945; Phillips et al., 1981).

However, Owens et al. (2011) reported total nitrogen losses of 35-94% by mass. These numbers are highly variable due the extreme variance in weather conditions, with flash events contributing more nutrient loss than slower melt events. Authors noted that it is possible for nearly all loss to occur in a single storm event (Klausner et al., 1976; Owens et al., 2011).

While these results can be staggering, it is worth noting that such losses are contingent upon fields exhibiting certain risk factors, as other studies have reported limited water quality impairment and a reduction of sediment loss relative to bare ground (Klausner et al., 1976; Young and Holt, 1977; Young and Mutchler, 1976). Findings appear to be a function of variance in local weather conditions, depth and type of soil freeze, the position of manure relative to the snowpack, and the timing of application relative to snow melt. Better understanding of these factors could lead to improved strategies for winter manure application.

2.2 Pathogens

Several varieties of pathogens are common in livestock excrement, though not all pose human health risks. Pathogens of concern include the following (USEPA 2004; Rogers and Haines 2005; Sobsey et al. 2006; Pappas et al. 2008; Bowman 2009):

- **Bacteria**: Escherichia coli (E. coli) O157:H7 and other shiga-toxin producing strains, Salmonella spp., Campylobacter jejuni, Yersinia enterocolitica, Shigella sp., Listeria monocytogenes, Leptospira spp., Aeromonas hydrophila, Clostridium perfringens, Bacillus anthraxis (in endemic area) in mortality carcasses
- **Parasites**: Giardia lamblia, Cryptosporidium parvum, Balantidium coli, Toxoplasma gondii, Ascaris suum and lumbricoides, Trichuris trichuria
- **Viruses**: Rotavirus, hepatitis E virus, influenza A (avian influenza virus), enteroviruses, adenoviruses, caliciviruses (e.g., norovirus)

As with nutrients, application of animal manure to impervious surfaces such as frozen ground can increase the risk of pathogen loss through runoff events relative to application in other seasons (Reddy, et al., 1981). Cool temperatures have been shown to improve the survival of fecal bacteria (Reddy et al., 1981; Kibby, et al., 1978). However, other researchers have reported that freezing conditions can be lethal to fecal bacteria during the course of field studies (Kibby, et al., 1978). While these reports hint at fecal bacteria being able to survive cool but not freezing conditions, Kudva, et al. (1998) reported *E. coli* surviving more than 100 days in manure frozen at minus 20^{o}C. Conversely, freezing and thawing of a soil manure mixture in was found to reduce *E. coli* levels by about 90% (Bicudo, 2003).

2.3 Antibiotics

In the early 2000s, it was estimated that approximately 60% to 80% of livestock and poultry routinely receive antimicrobials through feed or water, injections, or external application (NRC 1999; Carmosini and Lee 2008). Though new best management practices involving non-therapeutic use of antibiotics in livestock are likely to decrease these percentages, estimates for changes in these levels are not available. However, it is assumed that antibiotics will continue to play a therapeutic role in the livestock industry indefinitely and it is estimated that animals discharge 70-90% of antibiotics administered through excrement (Massé et al., 2014). Estimates are that 55% of antimicrobial compounds administered to livestock and poultry are also used to treat human infections (Benbrook 2001; Kumar et al. 2005; Lee et al. 2007). The utilization of such overlapping antibiotics has been cited as a potential cause of antimicrobial resistance (Sapkota et al. 2007), a grave concern in modern medicine (Levy and Marshall 2004; Sapkota et al. 2007). Land application of both solid and slurried excrement has been cited as a vector for introduction of antimicrobials into the environment (Boxall 2008; Klein et al. 2008).

Antimicrobials are hydrophilic and do not readily break down in the environment and are, consequently, at high risk of introduction into water bodies through runoff events (Chee-Sanford et al. 2009; Zounková et al. 2011). Critically, these compounds show high adsorptive tendencies in soils and clays (Chee-Sanford et al. 2009), thus providing a potential for interception by soil. Antimicrobials tend to degrade during manure storage, and the process appears to be more rapid under higher temperatures and aerobic conditions (Kumar et al. 2005; Lee et al. 2007; Boxall et al. 2008).

2.4 Air Quality

Few articles focus on the air quality impacts of winter manure application. Steenhuis et al., (1979) reported decreases in ammonia volitization rates for winter spread manure relative to spring due to lower temperatures. Lauer et al. (1976) showed that manure covered by snow had no signs of ammonia volatilization. These results suggested that limiting of ammonia volatilization may be critical to nutrient retention in soil, however, Williams et al. (2010) showed that manure applied under snow did not truly maintain this ammonia but lost it through runoff. No case studies have quantified the reduction of other odor causing compounds such as di-hydrogen sulfide in winter applied manure relative to other seasonal applications.

3. Management Practices

There is little standardization in regard to winter manure application. Although most states cite the NRCS conservation practice standard 590 for nutrient management (NRCS, 2013), the primary purpose of this document is to establish standards for all forms of nutrient application and there is only one by-line dedicated to winter manure application: "Nutrients must not be surface-applied if nutrient losses offsite are likely. This precludes spreading on: frozen and/or snow-covered soils, and when the top 2 inches of soil are saturated from rainfall or snow melt. Exceptions for the above criteria can be made for surface-applied manure when specified conditions are met and adequate conservation measures are installed to prevent the offsite delivery of nutrients." Consequently, there is great variety in management practices from state to state.

3.1 Best Management Practices

The National Handbook of Conservation Practices (NHCP) NRCS Code 590 articulates guidelines to optimize crop production while protecting waterways and maintaining soil quality. The guidelines describe necessary soil, tissue, and manure analyses. When considering manure application timing, farmers must attempt to correspond with optimum plant nutrient uptake as much as feasible. In regards to winter manure application, the document states that manure should not be applied on frozen, snow-covered, or saturated soil. When amending manure regulations, individual states will take the following into consideration: field slope, organic residue, cover crops, nutrients applied, and proximity of water. As a continuation of standard 590, the NRCS states that at a minimum the following factors should be considered before winter manure application.

- Field slope
- Organic residue and living covers
- Amount and form of nutrients to be applied
- Setback distances to protect local water quality
- Application timing

However, the acceptable range of these metrics are determined at the state level, leading to variations in implementation of best management practices (BMPs) (Table 2).

3.2 Policy

The ambiguity in standard practices for winter manure application has led to several different state policies. Table 2 lists northern U.S. states that have attempted to utilize risk management strategies or best management practices to address winter manure application issues. Table 3 lists states with manure application bans. States not listed have policies that are identical with NRCS standard 590.

State	Notes
Ohio	NRCS Standard 633 • 10 tons/acre limit • 90% surface residue cover required • No more than 20 contiguous acres • 200 ft setback • Additional restriction apply to fields with >6% slope
Pennsylvania	• 25% residue cover • 100 ft setback • No more than 5000 gal/A of liquid manure. • No more than 20 ton/A of dry non-poultry manure. • No more than 3 tons/A poultry manure • No greater than 15% slope
Michigan	• Michigan Generally Accepted Ag Management Practices (GAAMPS) • CAFO winter manure application must be approved. • CNMPs include an assessment of all fields by the Manure Application Risk Index (MARI) to determine runoff risk during winter application.
Illinois	• Illinois recommends avoiding applying manure on frozen or snow covered soil. • Winter manure application should be limited to areas with a 5 percent slope or less and where there are acceptable erosion control practices. • Manure should not be applied in the winter if the livestock wastes will runoff to the waters of the state.

Table 2: *States with Winter Manure Application Standards or Guidelines*

State	Ban Duration	Implementation Info
Vermont	Dec 15 – April 1	Established in 1995
Iowa	Dec 21 – April 1	Frozen and snow covered ground Emergency spreading is allowed
Maryland	Dec 15 – April 1	Slated for 2016 Enforcement (CAFO only)
Indiana	Dec 15 – April 1	Emergency spreading is allowed
Minnesota	Dec 1 – Thaw	Solid manure not included
Wisconsin	Frozen or Snowy Ground, February – March	Unless incorporated, Total ban - Liquid manure

Table 3: *States with Winter Manure Application Bans*

4. Winter Spreading Case Studies

Several case studies have been conducted to examine winter manure application. Table 4 summaries the studies and a brief description of each study, listed in chronological order, is provided below.

- To understand the effects of spreading cattle manure during the winter, Midgley and Dunklee (1945) conducted three field experiments and several laboratory trials. The field investigations were conducted at 3 sites, having fairly steep slopes of 8%, 10%, and 20%. The authors found that field slope had little impact on runoff losses. The potash runoff losses were greater than nitrogen and phosphorus losses combined and the addition of superphosphate or hydrated lime to fresh manure increased nitrogen runoff losses. Though the addition of straw to the manure lead to decreased nitrogen volatilization, this nitrogen was then susceptible to runoff losses. Despite the runoff potential, the authors suggested that farmers continue spreading manure daily because of the lack of storage resources. In addition to the runoff losses, volatilization of ammonia was also considered to contribute to large nitrogen losses from the manure.
- Hensler et al. (1970) spread fresh dairy manure onto field-scale plots and the resulting crop yields, nutrient recovery, soil fertility, and runoff were investigated. The researchers found that manure application consistently lead to high corn yields. When manure was incorporated into the soil after drying on the surface for a week, the yields were significantly lower. After fermented manure application, nitrogen recovery values were comparatively high and after anaerobic liquid manure application, phosphorus recovery values were comparatively higher. In general, winter manure application resulted in increased losses of nitrogen, phosphorus, and potassium when compared to spring manure application. Over the 2 year study, average runoff losses of nitrogen, phosphorus, and potassium were 10%, 6%, and 8%, respectively.
- Converse et al. (1976) applied dairy cattle manure at a rate of 2.25 kg/m2 to 10 alfalfa plots in late fall, mid-winter, or spring months. The nitrogen, total phosphorus, and potassium losses were not significantly different between treatment times. On average, nitrogen, total phosphorus, and potassium losses were greater on manured plots than controls. The average runoff on fall manured

Authors	Duration Of Study	Location	# of Plots	Plot Size (m)	Soil Type	Manure Type	Slope (%)	Cover	Tillage
Midgley and Dunklee (1945)	3-6 yrs	Vermont	N/A	92 m2		Fresh dairy Manure	8, 10, 20	N/A	N/A
Hensler et al. (1970)	2 yrs	Wisconsin	4	N/A	Silt loam	Fresh dairy Manure	11	None	Plowed on the contour
Converse et al. (1976)	3 yrs	Wisconsin	10	3 x 13.2	Silt loam	Solid dairy Manure	10-12	Alfalfa-grass mixture	N/A
Klausner et al. (1976)	3 yrs	New York	8	61 x 53.3	Silt loam	Dairy manure	2	Corn trash	N/A
Young and Mutchler (1976)	3 yrs	Minnesota	8	4.06 x 23.35	N/A	Solid dairy manure	9	4-corn, 2-new alfalfa with oat cover crop, 2- 6yr old alfalfa	Corn-fall plowed
Young and Holt (1977)	3 yrs	Minnesota						Tilled corn	Up and down slope
Philips et al. (1981)	6 yrs	Ontario	14	75.6 x 11.6	Sandy clay loam	Liquid dairy	0.8	Corn stubble	None
Steenhuis et al. (1981)	1 yrs	Wisconsin	8	13 x 3	Silt loam	Solid dairy manure	10-12	None	Plowed
Lorimor and Melvin (1996)	2 yr	Iowa	24	3.8 x 22	Silt loam	Liquid swine manure	2.9	12-short bean, 12-long corn stubble	N/A
Klausn Lewis et. Al. 2009	5 yr	New York		Various	Various	Various	Various	Various	Various
Komiskey, M.J (2011) (1976)	4 yr	Wisconsin	3	16 h.a.	Clay loam	Liquid dairy, solid beef	4-6	None	None
Owens L.B., et al (2011)	3 yr	Ohio	7	1 h.a.	Clay loam	Turkey Litter, Swine manure	7-13	Corn	Conservation Tillage
Stuntebek et. Al. (2011)	5 yr	Wisconsin	15	Various	Various	Beef and Dairy	Various	Various	Various

Table 4: *Summary of Winter-Spreading Field Studies Key Parameters and Results (adapted from Flemming et al 2000)*

plots was less than winter or spring applied plots. Nevertheless, the runoff measurements were greater on control plots when compared to manured land. Though production trends increased on the manured land, there was no significant difference between yields on manured and control plots.

- Klausner et al. (1976) conducted field plots with 3 different rates of winter-applied dairy manure for 3 consecutive years and the resulting inorganic nitrogen and total soluble phosphorus losses were examined. The 200 metric tons/ha rate resulted in approximately 4 times the amount of nitrogen and phosphorus runoff when compared to the 35 metric tons/ha rate. In 1972, the 200 metric tons/ha and 35 metric tons/ha rate were applied before snowfall while the 100 metric tons/ha rate was applied during active thaw. This demonstrated that manure applied during active thaw periods has a higher probability of nutrient loss by runoff than manure applied before snowfall.
- Young and Mutchler (1976) and later Young and Holt (1977) conducted field studies using the same soil plots to investigate the effects of solid manure application timing on nutrient loss. On plots averaging 9% slope the research team applied manure and examined the effects of 3 separate application timings on nutrient loss: fall spread and incorporated manure, fall spread on frozen ground and spring spread on top of snow. In both studies, the researchers noted that spreading manure on top of snow, rather than before a snowfall, resulted in less soil, water, and nutrient losses in the manured plots when compared to bare ground. This was attributed to the manure's ability to act as "mulch" that dispersed the force of raindrops in the spring season.
- Phillips et al. (1981) conducted a 6 year study investigating the roll of manure application rate and timing on nutrient surface and subsurface water. Liquid dairy manure was spread onto a 0.8% slope in fall, winter, and spring. Results showed that runoff values for all nutrients investigated (nitrogen, phosphorus, and potassium) were statistically significantly higher for winter spread plots than for spring and fall application plots.
- Steenhuis et al. (1981) investigated how nitrogen is lost when dairy manure is spread during winter months in lab and field experiments. Both the field and lab results demonstrated that most nitrogen is lost in soluble forms. For example, during the laboratory experiments, 75% of the soluble organic nitrogen and 3% of the particulate nitrogen was lost due to runoff. In the field experiments, most of the soluble nitrogen lost was lost during the first runoff event. The authors stipulated that if the soil is frozen and covered with ice or melting snow when manure is spread, high nitrogen losses will occur.
- Lorimor and Melvin (1996) investigated nitrogen losses in snowmelt runoff from fields applied with liquid swine manure with a 2.9% slope and with either bean or corn stubble cover. Plots were treated randomly with manure either in the fall (with incorporation), during early winter, during late winter, or during the spring. Runoff nitrogen losses were measured and expressed as a percentage of the manure- nitrogen applied with the average losses listed below.
  - » Fall-incorporated - 1.5%
  - » Early winter broadcast - 1.4%
  - » Late-winter broadcast - 10.3%
  - » Spring broadcast - 0.6%

  The authors stated that most of the loss was due to a single event wherein snow melt occurred two days after broadcast resulting in a 17.4% loss of applied manure. Due to the high risk of such flash events, the authors advised against applying manure during the winter. The authors also noted that the risk of runoff was greater in the corn stubble fields due to the increased volumes of snow. This was hypothesized to occur because the larger stubble acted as a catchment for blowing snow, trapping it in place and providing a greater volume of water available for spring melt.

- Gupta et al. (2004) evaluated the effects of tillage and timing of manure application on nitrogen leaching. Liquid dairy manure was applied either in the fall (before snow) or in winter (over snow with frozen soil underneath), with no manure under two tillage systems (no-till and chisel-plowing) used as controls. The researchers found that more nitrogen leaching resulted from the fall manure-applied, compared to the no-manure treatment. However, there was no statistical difference in N leaching between winter applied manure and the no-manure controls. In short, it appears applying to frozen ground inhibits leaching.
- Van Es et al. (2006) analyzed the impacts of various soil types, cropping systems, and times of manure application on nitrogen losses over 3 years. The nitrate concentration under maize appeared to be inversely proportional to application time. The later in the season manure was applied the lower the leaching risks with early and late spring showing the lowest leaching volumes. Fall manure application resulted in nitrate leaching losses above the USEPA Maximum Content Level. These concentrations were seen in greater quantity in sandy soil versus loamy soil and maize crops versus grass crops. Nitrate-N concentration was greater in loamy soil than clay soil.
- Ruiz Diaz and Sawyer (2008) considered the application of 2 different poultry manures on corn fields during the late fall, winter, and early spring. The resulting nitrogen availability, grain yield, grain nitrogen uptake, leaf chlorophyll meter, and soil nitrate were measured. The soil nitrate concentration was greatest for spring application and smallest for fall application. One explanation for this result is soil nutrient loss. Though manure source and application time differed, the resulting plant nitrogen availability, corn grain yield, grain nitrogen uptake, and chlorophyll meter reading were constant.
- Lewis and Makarewicz (2009) measured nutrient fluxes downstream of the Graywood Gully watershed leading to Conesus Lake. Winter manure spreading was halted in 2002-03, resumed in 2005-06 and then halted in 2007. Over the 5 year study, nonevent total phosphorus, soluble reactive phosphorus, TKN, and nitrate decreased, but the event didn't decrease within a year of halting manure application. Only a few days after restarting application, the soluble reactive phosphorus, nitrogen, and total phosphorus concentrations increased while total suspended solids didn't have a significant impact. TKN was lost from the watershed for 1 week after the application. Timing, topography, and weather conditions dramatically impact the effects of winter manure application.
- Komiskey et al. (2011) studied the effect of liquid dairy and beef manure application to frozen soil. This study shows a relationship between spreading and nutrient release that is highly dependent upon timing. Concentrations and losses of nitrogen and phosphorous were significantly greater in basins that had liquid dairy or solid beef manure applied less than one week before a runoff event. Concentrations were much lower for basins where liquid dairy manure/solid beef manure was applied in late fall/early winter. Greater than 80% of the phosphorus measured in runoff was dissolved.
- Owens et al. (2011) conducted controlled tests over 3 years at a USDA experimental research station. Two plots tested turkey litter, 2 tested liquid swine manure, and 2 used nitrogen fertilizer as a control. Applying manure at the rate of nitrogen needed for crops resulted in excess phosphorus. Phosphorus losses in surface runoff were greater than from controls and previous management with mineral fertilizer.

- Williams et al. (2010) applied manure to soil before, during, and directly after an artificial snowstorm to investigate how manure and snowpack interaction impacts nutrient losses. The results demonstrated that manure application before snowfall increased the losses of total nitrogen and ammonia in the snowmelt runoff. Manure application after snowfall resulted in a decrease in ammonia loss but an increased organic nitrogen, dissolved reactive phosphorus, and total phosphorus loss.
- Williams et al. (2012) applied dairy manure to soil surfaces at temperatures of 15.7°C, 4.8°C, and -1.1°C to analyze how soil temperature affects phosphorus losses in runoff and leachate as well as how manure application time impacts overwinter phosphorus losses. The loss of dissolved reactive phosphorus, total dissolved phosphorus, and total phosphorus increased as the soil temperature decreased. The winter treatment produced two times higher total phosphorus loss compared to the early fall application. Suggestions include spreading manure when the soil temperature is greater than 10°C
- Shappell et al. (2016) measured nutrient levels in 6 watersheds over 3 years. Two watersheds were set as a control with no manure application, 2 had swine manure, and 2 had turkey litter. Turkey litter was applied at a rate of 6.84 dry matter mg/L and swine manure was applied at a rate of 1.06 to 0.64 dry matter mg/ L. Total cumulative runoff was measured and found to be greatest in 2011 due to higher precipitation rates that year. Swine manure plots showed total nitrogen levels 3-4 times higher and unfiltered phosphorus levels 14 times higher than controls. Turkey manure plots showed total nitrogen losses were 27 times higher and total phosphorous losses were 45 times higher than controls.

In summary, the vast majority of studies suggest that winter application of manure increases loss of nutrients, (Komiskey et al., 2011; Lorimor and Melvin, 1996; Owens et al., 2011; Phillips et al., 1981; Thompson et al., 1979) with losses of up to 27% of applied phosphorus (Thompson et al., 1979) and 22% of applied nitrogen (Lorimor and Melvin, 1996). However, some studies have noted decreases in sediment loss with the application of solid dairy manure (Young and Mutchler, 1976), relative to bare soil. Though reducing nutrient loss appears to be an uncommon outcome of winter manure application, these findings demonstrate that the potential of soil and nutrient loss from winter manure application is greatly dependent upon field specific features as well as local weather. This is important, as winter manure application may always exist in some form (i.e. emergency spreading and application by non-CAFO farming operations) and may even be more environmentally desirable before the onset of soil freezing than application during a wet spring. Consequently, understanding BMPs to reduce the risk of nutrient losses is critical, as discussed below.

4.1 Best Management Practices and Winter Manure Application

With regard to the timing of application, authors have traditionally considered whether the manure is applied in early winter, before appreciable snowfall has settled on the ground, and in late winter with well-established snow and ice formations on the soil. Models and experiments conducted under controlled conditions have shown that late winter applications on top of snow and ice constitute a higher risk practice for nutrient runoff than does early winter "below the snow" applications (Smith et al., 2016; Vadas et al., 2009). This result has been verified at field scale as well (Lorimor and Melvin, 1996; Williams et al., 2010). However, at least one field study (Young and Mutchler, 1976) observed that late winter spreading decreased the mass of nutrients lost, though this appears to be an outlier.

Cover crops are often used to reduce velocity of runoff and promote settling of particulate matter while providing a vector for soluble nutrient uptake and sequestration. However, the advantage of effluent velocity reduction is negated if the crops are covered by snow or ice, and the nutrient uptake effect is negated by the fact that these crops are dormant through most of the spring thaw. Cover crops have also been shown to increase certain risk factors for nutrient runoff. Specifically, Lorimor and Melvin (1996) found that cover crops can act as a catchment for blowing snow and thus increase spring runoff volumes. Bechmann et al. (2005) found that multiple freeze-thaw cycles can trigger a release of soluble phosphorus that was previously bound in the cover crop biomass. Young and Mutchler (1976) noted that alfalfa fields stayed frozen longer than bare ground. However, Storey (1955) found that cover crops also have the ability to reduce the incidence and depth of impervious soil freeze events in the first place, thus improving vertical integration of melt water.

Other BMPs are often reported by researchers and are used by governing bodies but need further study. For instance, tillage practices, setback distances, and soil types are often reported by authors in studies as observed in Table 4. However, none of the studies reviewed investigated these factors as the primary variable of interest. As such, it is difficult to cross compare these factors across studies and derive scientifically based BMPs due to the presence of numerous confounding variables.

5. Summary & Conclusions

There are several parameters that ultimately determine the impact winter manure spreading will have on the environment, and how much of the nutrient content will remain in the soil after land application. These include but are not limited to: slope, soil type, depth of freeze, rate of thaw, depth of snow, presence of cover crops, tilling practices, manure moisture content, and timing of application. Because of natural variance in several of these conditions, it is difficult to isolate the relative effect of one parameter compared to another and, in some cases, these variations have caused contradictory research results. Furthermore, the inability to consistently isolate the effects of individual parameters leads to the possibility of conflating correlation with causation in study results. However, several general findings may still be derived.

The soil health benefits of winter manure application appear to be limited. The literature suggests that soil compaction and nitrogen volatilization can be reduced when applying to frozen soil but at the potential expense of nutrient runoff.

Most frozen soils have been shown to be impervious. Impervious soils carry a greatly increased risk of snowmelt causing a runoff event capable of carrying particulate matter, pathogens, and soluble compounds contained in winter spread manure. However, under select conditions, spreading, particularly of solid manure, in the winter has been shown to have little nutrient loss and a net positive effect on loss of sediment when compared to bare soil. The fate of these contaminants of concern is closely bound to the flow of melt water, so understanding the volume of potential meltwater, the permeability of soil, and proximity of surface water at the time of thaw is critical to understanding runoff risk. This runoff risk must further be juxtaposed with the site specific average risk of runoff of spring applied manure.

Cover crops are not as effective in mitigating nutrient loss from winter applied manure as spring or fall applied manure. Though it is often cited as a BMP, crop maturity may not be adequate at the time of thaw to act as a buffer against sheet flow of manure. Manure applied to heavy layers of snow or ice may run-off before cover crops are uncovered by the thaw and may be responsible for the increased accumulation of snow and ice on a field. Also, freeze-thaw cycles may increase dissolved phosphorus releases through interactions with the cover crop root zone.

Application of manure onto any frozen or snow covered surface carries a higher risk of runoff and subsequent loss of contaminates of concern into the environment than during fall or spring application. However this depends to some degree on the relative imperviousness of the bare ground (concrete, honeycomb, stalactite, or granular freezing patterns) and the pack density of the snow/ice.

With regard to potential pathogens, fecal bacteria appear to largely be destroyed in the presence of multiple freeze thaw cycles, though not all the literature confirms this result. Further study may be needed, as well as investigation into non-bacterial biological COCs.

Ammonia volatilization appears to be negated when manure is applied below snow, though ammonia can still be lost to runoff events. The fate of other odor causing compounds is understudied.

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