Quantifying the Impact of Seasonal and Short-term Manure Application Decisions on Phosphorus Loss in Surface Runoff

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ABSTRACT

Agricultural phosphorus (P) management is a research and policy issue due to P loss from fields and water quality degradation. Better information is needed on the risk of P loss from dairy manure applied in winter or the benefits of delaying manure application when runoff is imminent. We used the SurPhos computer model and 108 site-years of weather and runoff data to assess the impact of these two practices on dissolved P loss. Results showed winter manure application can increase P loss by 2.5 to 3.6 times compared to non-winter applications, with the amount increasing as the average runoff a field generates increases. Increased P loss is true for manure applied any time from late November through early March, with a maximum P loss from application in late January and early February. Shifting manure application to fields with less runoff can reduce P loss by 3.4 to 7.5 times. Delaying manure application when runoff is imminent can reduce P loss any time of the year, and sometimes quite significantly, but the number of times that application delays will reduce P loss is limited to only 3-9% of possible spreading days, and average P loss may be reduced by only 15% for winter-applied manure and 6% for non-winter applied manure. Overall, long-term strategies of shifting manure applications to low runoff seasons and fields can potentially reduce dissolved P loss in runoff much more than compared to near-term, tactical application decisions of avoiding manure application when runoff is imminent.

Agricultural nutrient management is a research and policy issue due in part to phosphorus (P) loss in runoff from fields and water quality degradation (Carpenter et al., 1998; Parris, 2011; Good et al., 2012). Manure applied without incorporation can be a significant source of dissolved P loss (Kleinman and Sharpley, 2003; Vadas et al., 2007), which is of particular concern (Baker et al., 2014). For surface-applied manure, maximum P loss occurs when manure with high available P is applied during times of high probability of runoff. In northern U.S. states and Canadian Provinces, winter and early spring are periods of frequent runoff from snowmelt and rain-on-snow events. In some states, winter application of dairy manure is common because it reduces the need for manure storage, allows time for spreading when there are fewer field activities, and reduces soil compaction from equipment when soil is frozen (Srinivasan et al., 2006). Due to frozen soil, winter-applied manure is typically not unincorporated. This combination of surface manure and high runoff potential has prompted states to restrict winter spreading to prevent loss of manure constituents, including P (Srinivasan et al., 2006). Studies of P loss in runoff from late-fall or winter-applied manure are limited, with most being observational at the plot to field scale. Most research was conducted before 1980 (Converse et al., 1976; Klausner et al., 1976; Young and Mutchler, 1976; Young and Holt, 1977; Phillips et al., 1981; Steenhuis et al., 1981), with some more recently (Hansen et al., 2000; Ulen, 2003; Lewis and Makarewicz, 2009; Komiskey et al., 2011; Owens et al., 2011). Observed P loss varied, generally because of variable weather and hydrology from year to year. This, combined with limited manure management treatments investigated, makes it difficult to develop scientifically-based application recommendations for late-fall and winter that address the variety of conditions or practices that may occur (Srinivasan et al., 2006). Thus, there remains a need for comprehensive analysis of the risk of P loss from late-fall and winter dairy manure application.

Outside of the winter period, it is also recommended to delay manure application when runoff risk is imminent to reduce the risk of P loss. Such delays assumedly allow manure more time to assimilate into soil (Hanrahan et al., 2009). The few studies investigating if more time between application and the first runoff event can decrease P loss have mixed results. Vadas et al. (2011) proposed that storm hydrology is more important than time between application and runoff for manure P loss. Uncertain weather forecasts can also make it difficult to time manure applications to avoid near-term runoff, especially since delays can affect timely emptying of manure storages. Therefore, it is not clear that manure management designed around timing application based on near-term weather is effective at reducing P loss.

Computer modeling can help assess the impact of both of these seasonal and short-term manure application issues (i.e., winter applied manure and application delays) on P loss because a variety of weather, hydrologic, and manure management conditions can be evaluated. Vadas et al. (2007; 2011) developed the SurPhos model to simulate surface application of manure and loss of dissolved P in runoff. SurPhos is unique because many field to watershed scale models do not estimate dissolved P loss directly from surface manure (Collick et al., 2016). Consequently, there has be no research evaluating P loss from winter applied manure using a model specifically designed for manure P loss, and SurPhos has not been tested for winter processes. Similarly, there has been no modeling effort to evaluate the impact of delaying manure application to avoid near-term runoff on P loss, especially in relation to seasonal strategies of avoiding periods of high runoff (e.g., winter). Therefore, our objectives were to i) assess if SurPhos reliably simulates dissolved P loss in runoff from late fall and winter-applied dairy manure, and ii) use the model to evaluate the impact of dairy manure application on dissolved P loss in runoff in different seasons and relative to the timing of near-term runoff.

Materials and Methods

SurPhos Model Description

SurPhos is a daily time-step model designed to be integrated into field or watershed models (Collick et al., 2016) to improve how they simulate surface application of manure and dissolved P loss in runoff. Thus, SurPhos does not simulate all processes that affect P availability and loss in runoff in a soil/manure system, namely crop growth, runoff generation, or soil erosion and particulate P loss. SurPhos requires input data for initial soil P content, the amount of manure applied, the moisture and P content of manure, daily average temperature, and daily precipitation and runoff.

SurPhos simulates surface manure application and four pools of manure P, water extractable inorganic and organic P (WEP_I and WEP_O) and non-water extractable inorganic and organic P (Non-WEP_I and Non-WEP_O). Only WEP_I and WEP_O are available for release during a rain or snowmelt event and loss in runoff. SurPhos also simulates inorganic soil P cycling and loss in runoff, but not soil organic P cycling. Users specify the day and rate of manure application, manure P content, and application method. After application, the model simulates manure decomposition and physical assimilation into soil, and conversion of Non-WEP_O, Non-WEP_I, and WEP_O into WEP_I or WEP_O. When rain or snowmelt occurs (i.e., liquid water interacting with manure), SurPhos simulates WEP_I and WEP_O release from manure as a function of the ratio of water volume to manure mass (cm^3 g^{-1}). Dissolved P in runoff is estimated by multiplying this released P by a unitless P Distribution Factor (P_d), which is a function of the ratio of runoff to water volume (rain and/or snowmelt as appropriate).

SurPhos simulates several mechanisms that affect the availability of manure P to loss in runoff for a given event. These are:

1. Manure decomposition, which decreases mass and coverage on the soil surface and changes the amount of WEP released during an event.
2. Conversion of manure non-WEP to WEP, which increases manure WEP available to loss in runoff.
3. Manure solids and P assimilation into soil, which decreases manure WEP available to loss in runoff. Assimilation also decreases manure mass and coverage on the soil, which affects manure P loss similar to (1).

The effect of timing of manure application on dissolved P in runoff is a function of how these processes interact.

SurPhos Model Testing for Winter Conditions

SurPhos has been tested for manure P loss in runoff (Vadas et al., 2007; Collick et al., 2016), but not for winter conditions and snowmelt runoff. We used the data of Komiskey et al. (2011) and Jokela and Casler (2011) from Wisconsin for this purpose. In the former study, P loss in runoff was monitored on a commercial farm over four winters (2003-2007) from three basins (6.8 to 16.0 ha) in no-till, corn/soybean rotations. Liquid dairy manure or solid beef manure was surface-applied to fields at different rates and times, but manure was applied at least once in all months from September to March over the four years (Figure 1). For the Jokela and Casler (2011) study, P loss was monitored over five years (2008-2012) from one field (1.6 ha) where liquid dairy manure (3-14% solids) was surface-applied in early November from 2008 to 2011 (Figure 2). We simulated both study conditions, using measured precipitation and runoff as well as reported manure application rates, times, P contents, and field area covered. We assumed WEP in dairy manure was 60% of total P, and 50% of total P in beef manure (Kleinman et al., 2005). We compared measured and simulated dissolved P concentrations in runoff for all reported events to assess if SurPhos reliably estimates dissolved P loss after surface manure application.

SurPhos simulates daily P release from manure based on how much liquid water interacts with manure solids. If runoff occurs, the model uses the ratio of this water amount to runoff amount to determine P loss in runoff. During non-winter periods, liquid water amount is measured rain. During winter, liquid water includes rain and/or snowmelt. In the monitoring projects, measured winter weather included daily temperature, rain, and snow (liquid water equivalent). We used these data to estimate a daily amount of liquid water that could interact with manure. To do this, we estimated daily snow water equivalent using measured snowfall data and estimated daily snowmelt. We estimated snowmelt using a degree-day method where the snowmelt rate was 2.5 mm per degree C (mean daily air temperature) greater than 0.0 (USDA-NRCS, 2004). We estimated how much snowmelt, as well as any rain, was absorbed by snow before it became free flowing water and interacted with manure. To do this, we assumed that the depth of fresh snow was 12 times the water equivalent depth and that snow could absorb water up to 6% of its depth. For example, if 100 mm of snow fell (actual snow depth), it could absorb six mm of water (either snowmelt or rain). If there was three mm of snowmelt (water equivalent) and two mm of rain, snow absorption capacity was reduced to one mm, and remained there until more snowmelt or rain occurred to decrease absorption capacity or new snow fell to increase capacity. We used a daily amount of liquid water present that exceeded snow absorption capacity to simulate interaction with manure. Finally, if measured runoff was greater than this unabsorbed liquid water amount, we increased snowmelt so it was 120% of measured runoff. This assumption applied to 67% of winter-period runoff events. This may seem high, but it is reasonable given that there were no measured data on rates of snowmelt.

We evaluated model performance using regression, Nash-Sutcliffe model efficiency, root mean square error (RMSE), and the ratio of RMSE to the standard deviation of observed values (RSR) (Moriasi et al., 2007; Bennett et al., 2013; Bolster and Vadas, 2013). For regression, we evaluated if slopes relating measured and predicted values were different than 1.0, and if intercepts were different from 0.0 ($p=0.05$). Nash-Sutcliffe efficiencies range from $-\infty$ to 1. An efficiency of 1 means a perfect match of modeled and observed data, zero indicates model predictions are as accurate as the mean of observed data, and less than zero is when the observed mean is a better predictor than the model. The RMSE is a measure of the average difference between predicted and observed values. The RSR varies from an optimal value of 0, which indicates zero RMSE and perfect model simulation, to a large positive value.

Quantifying P loss from winter-applied manure and fertilizer

After testing, we used SurPhos to quantify dissolved P loss in runoff from manure surface-applied at different times of the year. We collected measured precipitation and runoff data from seven, field-scale sites in WI, as described by Jokela and Casler (2011) and Good et al. (2012). Data included 108 site-years, with a site-year from October 1 to September 31. Data was collected between 2003 and 2012. We divided data into three groups of low, medium, and high runoff to represent site-years with different runoff potential. To do this, we summed precipitation and runoff data for all site-years from the winter period (December 1 to March 31) and determined the runoff to precipitation ratio of the sums. Site-years with ratios from 0-10% were in the Low group (n=36), 10-25% were Medium (n=37), and greater then 25% (maximum of 53%) were High (n = 35).

For each runoff group, we simulated a surface manure application on October 1, and ran the model for all site-years, with the same application day each year. We then reset the model and repeated this procedure, but with manure applied October 2. We continued until all days of the year were simulated. This allowed us to quantify changes in runoff P loss depending on when manure is applied over many years of weather and hydrology. We used a liquid dairy manure application of 5611 kg ha^{-1} (dry matter equivalent), with 6% dry matter, 0.7% total P, and a WEP to total P ratio of 0.5. This is a P application of about 39 kg ha^{-1}.

We conducted these simulations with one variation representing the effect of delaying manure applications during periods of active runoff (Sharpley, 2016). We conducted all simulations as described above, but delayed manure application if there was runoff in the following two days. For example, if manure was to be applied October 1, but there was runoff on any day from October 1 to October 3, application was delayed until the next day when there was no runoff for the following two days. We conducted such simulations for runoff-free periods of two, four, and six days.

Results and Discussion

Model Testing

Figure S1 shows measured data from Komiskey et al. (2011) for manure application dates and runoff dissolved P concentrations. The greatest runoff P concentrations (~8-12 mg L^{-1}) occurred for snowmelt soon after manure application. This occurred for Basins A and B in February 2004 from a liquid dairy manure application, for Basin B in March 2007 from a beef manure application, and for Basin C in January through March 2005 from several beef manure applications. For the Jokela and Casler (2011) data, runoff dissolved P was greatest (~3-5 mg L^{-1}) in the first events after manure application, but only once in November 2010 did a runoff occur within a few days after application (Figure S2). The other, "first" events were two to four months after application.

Of interest is whether manure applied in late fall or early winter (November – January) can substantially increase P in runoff that does not occur until late winter or early spring (February-March). For the Jokela and Casler (2011) study, manure applications in early November increased dissolved P in the first runoff even if it did not occur until months later (Fig. S2). For Komiskey et al. (2011), there were only two times that such conditions occurred. These were for manure applied in Basin A in December 2005 and early January 2006 with the first runoff in early March 2006, and for manure applied in Basin C in December 2006 with the first runoff in early March 2007. For Basin A, March runoff P concentration was 6.6 mg L^{-1}, which was much greater than summer dissolved P (~1.0 mg L^{-1}). For Basin B, March runoff P was ~3.0 mg L^{-1}. These studies suggest that winter-applied manure can increase dissolved P in runoff that occurs even two to four months after application. For this to happen, there needs to be little to no liquid precipitation or snowmelt between application and the first runoff event that would otherwise leach P from manure into soil. Due to cold temperatures, there is also little to no physical assimilation of manure and its P into soil. The lack of these two processes leaves manure P available for when runoff occurs.

Figure 1 shows measured and simulated data for runoff dissolved P from Jokela and Casler (2011). Data (n=102) had about half of events from snowmelt. Mean observed runoff dissolved P concentration was 0.43 mg L^{-1}, with 70% of observations less than 0.25 mg L^{-1}. The regression slope relating measured and predicted values was greater than 1.0, but the intercept was not different from 0.0 (p=0.05). The Nash-Sutcliffe efficiency was 0.64, the RMSE was 0.46 mg L^{-1}, and the RSR was 0.59. Moriasi et al. (2007) provide guidelines for model performance based on NSE and RSR, and would classify the NSE as satisfactory (NSE < 0.50 is unsatisfactory) and the RSR as good (RSR > 0.60 is satisfactory and >0.70 is unsatisfactory). Both classifications are for monthly time-step data, which Moriasi et al. (2007) report typically have better performance statistics than daily data. For our daily statistics to be classified as satisfactory and good shows SurPhos was reliably simulating dissolved P in runoff from manure for these winter conditions.

Figure 2a shows measured and simulated data for runoff dissolved P from Komiskey et al. (2011). Data (n=93) represent about 40 runoff events, with only 11 events outside winter. The regression slope relating measured and predicted values was not different from 1.0, and the intercept not different from 0.0 (p=0.05). However, the Nash-Sutcliffe efficiency was -2.55, the RMSE was 4.52 mg L^{-1}, and the RSR was 1.87, which do not suggest reliable P loss predictions. However, visual inspection shows two groups of data of consistent over-prediction and under-prediction (shown by different symbols in Fig. 2a). The under-prediction group was for runoff following liquid manure application on snow in February 2004, and the over-prediction group was for solid beef manure applications in winter 2005 and 2007. We made two, physically reasonable assumptions for these two data groups to see their effect on model performance. These were:

1. SurPhos assumes that liquid manure with less than 15% solids infiltrates the day of application, leaving only 40% of manure P on the surface for loss in runoff. For liquid manure applied in 2003 and 2004 on unfrozen soil, we retained this assumption because there was no reason to assume differently. This is consistent with conditions from Jokela and Casler (2011). For liquid manure applied in February 2004 to snow-covered soils (under-prediction group),

we eliminated this liquid infiltration assumption so snow absorbed the manure liquid and kept all P available for loss (Singh et al., 1997).

2. Unpublished data from our on-going lab-scale experiments of P leaching from solid manure during snowmelt and loss in runoff suggest melting snow water only partially interacts with solid manure. Compared to rainwater that fully interacts with manure, this partial interaction (about 20%) results in less P leached out of manure and thus less P loss in runoff. Thus for snowmelt events, we assumed melting snow interacts at only a 20% rate with solid manure (over-prediction group).

Figure 2b shows measured and simulated data for runoff dissolved P with the above two assumptions included. The slope of the regression line was less than 1.0, but the intercept was not different from 0.0. The Nash-Sutcliffe efficiency increased to 0.65 (good), the RMSE decreased to 1.42 mg L^{-1}, and the RSR decreased to 0.59 (good). The RMSE is still somewhat high, which may be because the study was conducted on a production farm and there was more uncertainty about manure field operations. Predictions for solid beef manure were still somewhat high and somewhat low for liquid manure. Clearly, model input data for manure characteristics and assumptions for manure interaction with soil and snowmelt can greatly affect predictions. However, prediction results from Figure 2b and Figure 1 for Jokela and Casler (2011) together suggest SurPhos can reliably estimate dissolved P loss in runoff for winter-applied manure.

Hydrology of runoff data sets

Figure 3 shows monthly average precipitation and runoff for the High, Medium, and Low runoff groups. In all groups, November, December, and January were months of lower precipitation and little runoff. This is somewhat due to our accounting for winter precipitation only when snowmelt occurred and not the day snow fell. Mid-winter to early spring consistently had runoff, but the importance of this period relative to the entire year varied between groups. For the High group, about 75% of annual runoff occurred in February, March, and April, with the remaining 25% mostly in July, September, and October. For the Medium group, about 50% of runoff occurred in February, March, and April, with the remaining 50% mostly in July, September, and October. For the Low group, about 30% of runoff occurred in February, March, and April, with the remaining 70% distributed over summer and early fall. Overall, differences in annual runoff were more due to variability in winter runoff than non-winter runoff. Non-winter runoff averaged over all site-years was more similar (High = 31.9 mm, Medium = 39.6 mm, Low = 17.3 mm) than winter runoff (High = 96.8 mm, Medium = 35.5 mm, Low = 7.0 mm)

Site conditions and weather are the two main drivers of runoff. The majority of runoff data came from two sites, in Stratford (central WI) on a somewhat poorly drained silt loam, and Platteville (southwest WI) on a well-drained silty clay loam. Of 24 site-years in Stratford, 12 were in the High group and 11 in the Medium group, which corresponds to the site being somewhat poorly drained. Of the 61 site-years in Platteville, 11 were in the High group, 24 in the Medium group, and 26 in the Low group, which corresponds to the site being well drained. Therefore, sites will tend toward more or less runoff given dominant soil conditions. However, of the six calendar years monitored in Stratford (2006-2012), nine of the 11 Medium runoff site-years occurred in the same three calendar years, and nine of the 12 High runoff site-years occurred in the other three calendar years. For Platteville, of the eight calendar years monitored (2003-2011), nine of the 11 High runoff site-years occurred in the same two calendar years, while those calendar years had only one Medium runoff site-year and no Low site-years. Therefore, weather will determine whether runoff tends towards the greater or lesser of a site’s potential. It may be possible to determine if a field should not receive winter-applied manure because soil properties create a high runoff risk. However, it may be difficult to determine if a field that could safely receive winter-applied manure will have high or low runoff for any given year.

Quantifying P loss from manure applied in different seasons

Figure 4 shows simulated P loss data for the High runoff group. Data points represent annual P loss when manure was applied on that day, and not days that runoff occurred. The figure shows maximum, minimum, and average annual P loss for each application day. The P loss ranged from more than 6 kg ha^{-1} to essentially zero when manure was applied after March and no runoff occurred the rest of the annual period. Greatest P loss was from late November through early March. During this winter period, maximum, minimum, and average P loss were consistently greater than in the non-winter period, and were consistently high (minimum values always > 0.4 kg ha^{-1}, average values always > 2.0 kg ha^{-1}, maximum values always > 5.0 kg ha^{-1}). These results correspond to a period of consistently high runoff risk in all site-years, as well as prolonged manure P availability due to low temperatures and little manure assimilation into soil. Figure 3 shows that for the High group, February and March have the greatest runoff, but Figure 4 shows that manure applied before this period, even two months earlier in November and December, has an elevated risk of P loss. It is only after early March that manure P loss decreases substantially. Figure 4 shows high manure P loss can occur in non-winter periods due to manure application shortly before runoff events, but on average the risk of P loss is much less during the non-winter period (April through early November).

For the Medium runoff data, results were similar to those for the High runoff group (Fig. S3). Winter was a period of consistently elevated runoff risk, although minimum P loss indicates there can be years of little winter runoff. While the non-winter period still represented a time of relatively less P loss, the greatest maximum P loss occurred during this period. Manure P loss in the Low group was consistently much less across the entire annual period than for Medium or High runoff sites (Fig. S4). For the Low group, the dominance of winter-period manure P loss was much less, which in turn increased the importance of non-winter manure P loss.

Table 2 summarizes the difference in dissolved P loss in runoff for manure applied in winter or non-winter periods for the three runoff groups. Data averaged over all site-years show the risk of P loss from winter-applied manure is 2.5 to 3.6 times that from non-winter manure. When comparing average annual P loss for the three runoff groups, P loss increases by 3.4 to 7.5 times as runoff increases. Such quantitative data can provide valuable information to producers or policy makers when developing manure application strategies. For example, while moving manure application out of the winter can help decrease P loss, applying manure to fields with less runoff potential may be more beneficial.

We note that our simulations assume a liquid manure application where manure liquid infiltrates into the soil on the day of application and makes 60% of the manure P unavailable to direct loss in runoff. We eliminated this assumption when simulating the Komiskey et al. (2011) data for liquid manure applied on snow. If we carried this elimination into our simulations using the High, Medium, and Low runoff group data, it would increase simulated winter P loss in proportion to the extra amount of manure P on the surface (60% in this case). Thus, P loss from winter-applied liquid manures can be even greater than that estimated in Figures 4, S3, S4, and Table 2. Conversely, the risk of winter P loss may be less than that presented if solid manure is applied and there is only partial interaction of snowmelt water with manure.

Quantifying the impact of delaying manure application on P loss

Table 1 presents results for annual P loss for the High runoff group only for zero, two, four, and six-day delays in manure application due to near-term runoff. From a long-term perspective (data averaged over all 365 application days and all 35 site-years, n=12,775), delaying manure application to avoid runoff generally reduced annual P loss. The greatest reduction was for a 6-day delay, but from an average annual loss of 1.25 kg P ha^{-1} to only 1.11 kg P ha^{-1}. From this long-term perspective, delaying manure application consistently decreased P loss only during a period from late January to early April (winter period in Table 1). Delaying manure application to avoid runoff could increase time for manure to integrate into soil, resulting in less manure P on the surface. However, this is a minor mechanism for a six-day period and not likely during colder periods with little biological activity. The more important mechanism for less manure P on the surface is manure exposure to non-runoff producing rain or snowmelt that transfer P from manure into soil.

Delaying manure application because of near-term runoff can change P loss at any time of the year. However, the opportunity for producers to use such application delays to reduce P loss may be limited. Table 1 shows that for P loss averaged over all application days and site-years of High runoff data (n=12,775), delaying manure application changed annual P loss more than 0.1 kg ha^{-1} on only as many as 12.4% (six-day delay) of possible application days. On 9.1% of those days, delaying application reduced P loss, but P loss increased on the other 3.3%. Shorter application delays (two-day and four-day) changed P loss less. Phosphorus loss increased because delaying application to avoid one runoff event exposed applied manure to a larger event beyond a given delay period. However, Table 1 shows that the potential to reduce P loss by delaying manure application was always greater than the potential to increase P loss. For days when delaying application reduced annual P loss by more than 0.1 kg ha^{-1}, the average decrease was as much as 1.73 kg P ha^{-1}, with a maximum decrease of 5.97 kg ha^{-1}. When delaying application increased annual P loss by more than 0.1 kg ha^{-1}, the average increase was as much as 0.47 kg P ha^{-1}, with a maximum increase of nearly 2.35 kg ha^{-1}. As expected, the impacts of delaying manure application on P loss were less for the Medium and Low runoff groups compared to the High group.

Results suggest manure application should indeed be delayed if runoff is imminent, and that doing so could decrease annual P loss substantially. However, the frequency of opportunities to decrease manure P loss by delaying application based on near-term weather is likely limited, and delaying application could possibly increase P loss. A strategic approach of applying manure in seasons of low runoff is more likely to reduce P loss than short-term decisions based on weather.

Summary

We used the SurPhos manure P runoff model to quantify the impact of seasonal and short-term manure application decisions on dissolved P loss. For regions with significant runoff from snowmelt, winter manure application can substantially increase the risk of P loss, due to extended periods of high manure P availability and consistent runoff. The risk of increased P loss is true for manure applied any time from late November through early March, with a maximum risk for manure applied in late January and early February. Shifting manure application to fields with lower runoff potential and seasons of lower runoff likelihood can greatly reduce the risk of manure P loss. Such shifts would be part of a management strategy designed around suitable soil types and crop rotations that allow manure application in late spring, summer, and early fall. Delaying manure application when runoff is imminent can help reduce the risk of runoff P loss at any time of the year, and perhaps substantially so. However, the number of opportunities for producers to actively use near-term application delays to reduce P loss is limited. Finally, appropriately developed and applied simulation models, such as SurPhos for P loss from surface-applied manures, are useful to help quantify a range of conditions and management practices and provide more robust information for producers and policy makers. However, our model results clearly show that model input assumptions for manure characteristics and assumptions about manure interactions with soil and snowmelt can greatly affect P loss predictions, and the accuracy of such data and assumptions is critical.

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Table 1. High runoff group results for effect of manure application delays.

Time Period	Required Number of Runoff-free days after Application			
	0	2	4	6
Average P Loss for Full-year period (kg ha^{-1})	1.25	1.20	1.14	1.11
Average P Loss for Winter Period (kg ha^{-1})	2.40	2.29	2.16	2.06
Average P Loss for Non-winter Period (kg ha^{-1})	0.67	0.65	0.63	0.63
% of days (n=12275) when application delay changed P loss by more than 0.1 kg ha^{-1}	--	4.8	9.1	12.4
% of days (n=12275) when application delay reduced P loss by more than 0.1 kg ha^{-1}	--	3.6	6.9	9.1
Average decrease in P loss (kg ha^{-1}), max in parentheses, when application delay decreased P loss by more than 0.1 kg ha^{-1}	--	1.48 (5.97)	1.69 (5.97)	1.73 (5.97)
% of days (n=12275) when application delay increased P loss by more than 0.1 kg ha^{-1}	--	1.2	2.2	3.3
Average increase in P loss (kg ha^{-1}), max in parentheses, when application delay increased P loss by more than 0.1 kg ha^{-1}	--	0.35 (2.13)	0.45 (2.34)	0.47 (2.35)

Table 2. Summary of simulation results showing the difference in dissolved P loss in runoff from winter-and non-winter applied manure for the three runoff group data sets, as well as the difference in annual P loss for the High and Medium runoff groups compared to the Low group. Data represent P loss average over all weather years in a data group.

Runoff Group	Winter P Loss (kg/ha/yr)	Non-Winter P Loss (kg/ha/yr)	Season Difference	Annual Runoff Difference over Low
Low	0.28	0.11	2.5x	--
Medium	1.01	0.35	2.9x	3.4x
High	2.40	0.67	3.6x	7.5x

Figure Captions

Figure 1. Measured and simulated runoff dissolved P concentrations for the data of Jokela and Casler (2011).

Figure 2. Measured and simulated runoff dissolved P concentrations for the data of Komiskey et al. (2011), with a) no model input assumptions, and b) model assumptions that liquid dairy manure does not infiltrate into soil when snow is present, and winter-applied solid beef manure had only 20% interaction with melting snow water and thus less P leaching and loss in runoff.

Figure 3. Average monthly measured precipitation and runoff data from several WI sites. Data are divided into High, Medium, and Low runoff groups, with ~35 site-years per group.

Figure 4. Simulated annual dissolved P loss in runoff for the High runoff group data. Each data point represents annual P loss when manure was applied that day. Lines show average, minimum, and maximum simulated P loss for the ~35 simulation years. Gray shaded area is one standards deviation from the average.

Supplemental Figure 1. Data from the study of Komiskey et al. (2011) showing runoff dissolved P concentrations over time. Vertical lines indicate times of manure application.

Supplemental Figure 2. Data from the study of Jokela and Casler (2011) showing runoff dissolved P concentrations over time. Vertical lines indicate times of manure application.

Supplemental Figure 3. Simulated annual dissolved P loss in runoff for the Medium runoff group data. Each data point represents annual P loss when manure was applied that day. Lines show average, minimum, and maximum simulated P loss for the ~35 simulation years. Gray shaded area is one standards deviation from the average.

Supplemental Figure 4. Simulated annual dissolved P loss in runoff for the Low runoff group data. Each data point represents annual P loss when manure was applied that day. Lines show average, minimum, and maximum simulated P loss for the ~35 simulation years. Gray shaded area is one standards deviation from the average.