An Exploratory Analysis of Edge-of-Field Phosphorus Losses

by:

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A thesis submitted in partial fulfillment of

the requirements for the degree of

Master of Science

(Agroecology)

at the

UNIVERSITY OF WISCONSIN MADISON

2021

APPROVED BY:

MASTERS

The University of Wisconsin-Madison
The Graduate School

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Agroecology MS

For: Fall, 2021

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The undersigned report that all degree requirements

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ACKNOWLEDGEMENTS

First and foremost, I would like to thank Dr. Matt Ruark and Dr. Anita Thompson for their guidance and support throughout this project. Their expertise and encouragement have allowed me to grow both professionally and personally. Throughout the COVID-19 pandemic, they have provided the support and resources necessary to make it through these wild months. I appreciate their flexibility and commitment to this project as we have all had to adapt. I would also like to thank Dr. Francisco Arriaga for sitting on my committee and providing edits and advice for my thesis.

Second, I would like to thank the teams at Discovery Farms Wisconsin (Tim Radatz, Amber Radatz, Tim Cooley), Discovery Farms Minnesota (Tim Radatz), USGS (Todd Stuntebeck), and others involved in the Great Lakes Restoration Initiative (Christopher Winslow, Craig Stow, Felix Martinz, and many others). Their partnership made this work possible, and I appreciate all who have been involved in the data collection and processing that have made this extensive dataset. Likewise, their counsel throughout the project has been helpful.

Third, I would like to send a special thanks to Emily Oldfield who has guided me through the process of creating Linear Mixed Models and provided code, advice, and support through the last several months.

Fourth, I want to show my appreciation to my lab mates, Agroecology cohort, and others in the Soil Science department for all their support over the past two years. Some of my favorite memories of this experience involve the other students that surrounded me. I appreciate the stimulating conversations as well as the goofy moments I have had with all of you.

Finally, I would be remiss to not extend thanks to my family and friends for their emotional support throughout these two years.

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ABSTRACT

Evaluating how weather, farm management, and soil conditions impact phosphorus (P) loss from agricultural sites is essential for improving our waterways while maintaining agricultural productivity. In this study, rainfall characteristics, manure application timing, tillage, surface condition, and soil test phosphorus have been analyzed to determine their effects on total phosphorus and dissolved phosphorus loss. The University of Wisconsin Discovery Farms and Discovery Farms Minnesota have been monitoring edge-of-field nutrient losses across 22 sites, totaling 125 site-years worth of runoff data. Single and two-factor analysis were used to identify key weather, management, and soil condition factors and their impact on phosphorus loss. Multilevel linear mixed models (LMM) were then used to evaluate the influence of those factors on total and dissolved phosphorus losses. We found that during frozen conditions, dissolved phosphorus (DP) was the large portion of total phosphorus (TP) loss, and during nonfrozen conditions, particulate phosphorus (PP) was the large portion of TP loss. The timing of manure applications is significant to TP and DP loads and concentrations, but high amounts of P loss can be seen long after the initial manure application. No till (NT) increased phosphorus loss compared to conventional tillage (CT) and reduced tillage (RT), particularly when runoff occurs due to rainfall on frozen ground or snowmelt. RT also had higher amounts of P loss compared to CT. Soil test phosphorus (STP) was high based on agronomic standards in the majority of sites at both the 0-5cm and 0-15cm depths. The least amount of P loss occurs when a crop has reached canopy cover until harvest, when compared to residue and no cover conditions. TP loads and concentrations are highest during no cover conditions, whereas DP loads and concentrations are highest during

residue conditions. LMMs are a helpful statistical method for large, unstructured datasets such as the one in this study, allowing for an understanding of the relative effect of different environmental conditions and farm management practices. Ultimately, this study provides helpful information on how particular weather conditions, management practices, and soil conditions influence P loss in agricultural sites.

INTRODUCTION:

Phosphorus (P) is an essential nutrient for crops but is not abundantly found in soils without additions from fertilizers or manures. Manure is frequently applied to croplands as a way to add P to the soil, reduce soil compaction, and reduce the need for manure storage structures (Srinivasan et al., 2006). However, excess manure application increases the risk of P being transported from the site in runoff and into the waterways, especially when unincorporated into the soil (Allen and Mallarino, 2008; Withers et al., 2001). P loss from nonpoint sources such as agricultural fields contribute to the eutrophication of rivers and lakes (Carpenter et al., 1998; Sharpley et al., 1993). Tools such as the Runoff Risk Advisory Forecast have been created to help farmers plan their manure applications with the goal of reducing the amount of runoff. Understanding the best time to apply manure and avoiding application before rainfall or snowmelt can reduce P loss, while still providing the benefits pertaining to manure applications. This is particularly important in cold climates where winter manure applications are common and high amounts of runoff occur during mid-winter and spring thaws (Srinivasan et al., 2006; Stuntebeck et al., 2011; Good et al., 2012).

Best management practices (BMPs) help reduce runoff and nutrient loss. Evaluating the effectiveness of BMPs, such as manure application timing, reducing tillage, increasing surface cover, and monitoring soil test phosphorus (STP) is important to reduce P from agricultural sources. Studies have investigated the timing of manure applications and P loss from agricultural fields mostly through laboratory experiments, plot scale studies, and models. Increasing the time between manure application and a runoff event allows for the manure to infiltrate the soil and can reduce P loss. In a laboratory rainfall simulation experiment, Cherobim et al. (2017) found that TP and DP losses were higher when rainfall occurred 24 hours after manure application compared to 7 days after manure application. Similarly, a plot-scale study found that nutrient concentrations were higher in runoff events close to nutrient applications (Owens et al., 2010). Findings from Vadas et al. (2011) suggest that intense rainfall events 30 days or more after a manure application can cause similar amounts of P loss as a runoff event that occurs right after a manure application. These studies demonstrate that while P loss does decline with time since manure application, more field scale studies are needed to further understand how the timing of manure applications impact P loss in runoff to improve farmers' decision-making process (Singh et al., 2020).

Likewise, studies have been conducted to analyze the effects of tillage, surface cover, and STP on P loss. No till and reduced till are recommended practices to reduce runoff (Palm et al, 2013). However, previous studies have shown that no till (NT) and other conservation tillage practices can lead to high concentrations of P in runoff, especially in cold climates (Tiessen et al., 2010; Sharpley et al., 1993). The amount of surface cover also plays a role in nutrient transport from agricultural fields. Studies have shown that increasing the amount of surface cover can reduce nutrient loss by providing protection from raindrop impact and slowing runoff (Blanco-Canqui and Lal, 2009). However, these covers are a potential source of P as they decompose (Elliot, 2013). Furthermore, recurrent manure applications can lead to the accumulation of soil P, which is linked to higher amounts of P runoff (Andraski et al., 2003; Baker et al., 2017). These increases in P loss are further amplified in NT or reduced tillage (RT) systems (Kleinman et al., 2011).

Previous research that analyzed edge-of-field data have used factorial experimental designs on an annual or seasonal scale to understand how management practices impact nutrient losses (Van Esbroeck et al., 2016; Tomer et al., 2016; Aryal et al.,2018). These studies manipulate a few variables across two or three sites to see how they influence nutrient losses on a field scale. In comparison, this study uses an unstructured sampling approach, with data collected by Discovery Farms Wisconsin and Discovery Farms Minnesota to understand the effects of management practices and weather conditions on P losses on an event basis. Previously, studies have analyzed Discovery Farms data using nonparametric analysis based on ranked data in frozen conditions (Kominsky et al., 2011) and regression tree analysis on a seasonal basis (Zopp et al., 2019) to understand P losses. These approaches provide insight on how frozen conditions influence P runoff. They also highlight the need for further investigation on how management and weather conditions interact leading to P loss on an event basis.

An alternative approach to analyzing unstructured data are multilevel linear mixed models (LMM). LMM are used in ecological studies and are a form of multivariate analysis that allows for comparisons between both continuous and categorical data. While not commonly used in agricultural research, they can be helpful statistical methods to understand the impact of environmental and management practices while accounting for random factors. A meta-analysis by Qian and Harmel (2015) showed how multilevel models could be used to assess the effectiveness of crop-specific conservation practices to reduce P runoff. Practices are compared to quantify their effect on runoff on a field scale and evaluate which factors have the largest influence on P losses.

Long term edge-of-field monitoring is important in evaluating the environmental and management factors that either cause or help reduce P loss. This study explores edge-of-field phosphorus loss on an event basis throughout WI and MN using observational data collected from the farmer-led Discovery Farms Wisconsin and Discovery Farms Minnesota programs. The data reflects a range of management and environmental conditions, providing a deeper understanding of how these conditions affect water quality. The objectives of this study were to i) construct a dataset consisting of edge-of-field surface runoff events and the corresponding management, surface condition, and rainfall factors, ii) determine the effects of runoff, manure applications, tillage, surface condition, and soil test phosphorus using single factor analysis to assess edge-of-field phosphorus losses, iii) assess the relative importance of environmental and farm management factors on phosphorus loads and concentrations in edge-of-field runoff using linear mixed models.

MATERIALS AND METHODS:

Site Descriptions and Dataset Construction

Discovery Farms Wisconsin and Discovery Farms Minnesota, in partnership with U.S. Geological Survey, have collected 125 site years (2004 - 2019) of event-based edge-of-field surface runoff data across 22 sites (n=1339). Figure 1 shows the location of the sites in Wisconsin and Minnesota. These sites represent a range of farming practices, topography, and soil types in the Midwest. A combination of agronomic, event-based edge-of-field runoff, and weather data were compiled in this dataset.

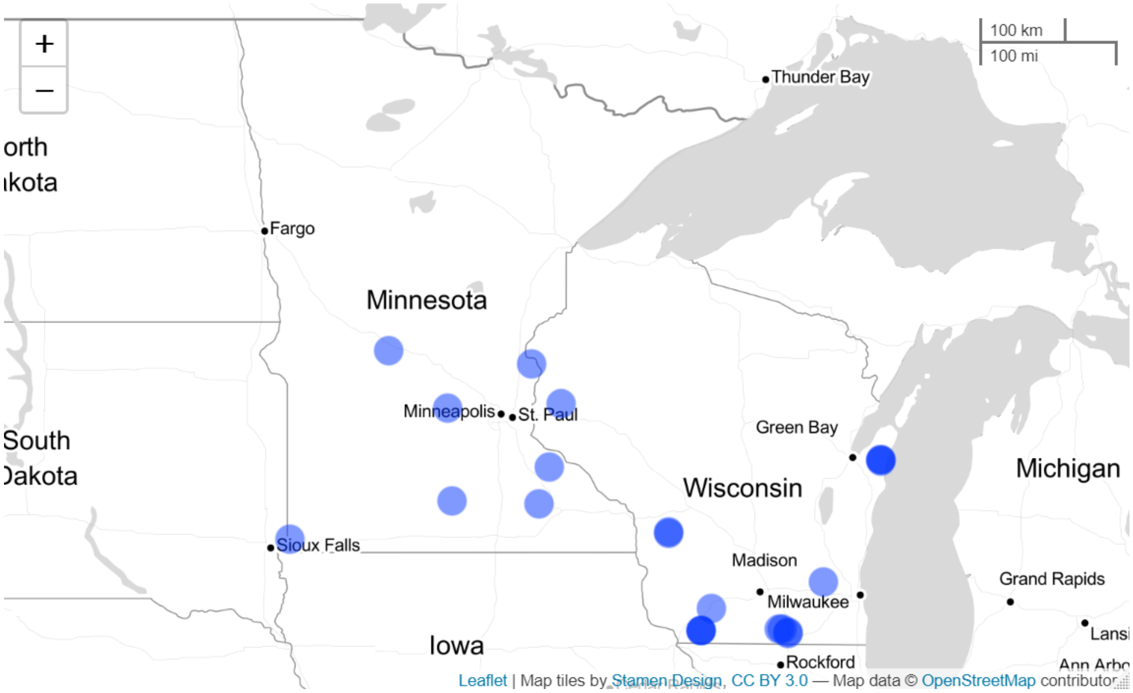

Figure 1. Map of Discovery Farms Sites in WI and MN. Light colored dots represent one site, darker colored dots represent three sites.

Farm management data were collected by Discovery Farms Wisconsin and Discovery Farms Minnesota. These data described all of the management practices that occurred on each site throughout the years the farm participated in the study and included: crop type (defined as what was planted for the growing season until the next year's planting date), tile drainage, tillage (long-term no till, reduced tillage which includes vertical or strip tillage or tillage every other year, and conventional tillage where at least one tillage pass occurred each year), manure and fertilizer application timing and rate, surface condition, and soil condition.

The surface condition category captured the state of the field at the time of the runoff event. This considered both the tillage history of the field and the amount of cover on the field. The surface condition categories include: (i) Tilled - Crop, (ii) Tilled - No Cover, (iii) Tilled - Residue, (iv) No Till - Crop, (v) No Till - No Cover, (vi) No Till - Residue. The tilled categories included both conventional tillage and reduced tillage. The no till category was long-term no till. The surface was categorized as "crop" during the time between canopy closure of the current crop, and a subsequent tillage pass or the harvest of corn silage. The crop stage stared at canopy cover for the canopy's potential to stop or slow raindrop impact on the soil surface, reducing soil displacement. For corn, the estimated canopy closure date was June 20th, for soy and pea this date was July 15th, and for alfalfa this date was June 20th. When there were multiple crops planted at the site, crop would start when the crop planted on over 50% of the site reached canopy cover. No cover represented when the field was fallow, either following a tillage pass or the harvest of corn silage. Residue represented time periods when plant matter was left on the field without any tillage occurring, or cover crops were planted on the field. Soil condition data included: soil type, hydrologic group, drainage class, soil condition (frozen or non-frozen), and soil test phosphorus (tested at 0 - 5 cm and 0-15 cm depth). Soil condition was determined using soil temperature probes (Stuntebeck et al., 2008).

To understand the influence of farm management practices on runoff, the days between a management practice and the following runoff events were counted. The management practices included: harvest, tillage, manure application, P fertilizer application, any P application, or any nutrient application. Each runoff event that occurred after the management practice had the specific number of days between the management event and runoff event recorded. Likewise, the number of runoff events between each management practice and an individual runoff event were counted and included in the dataset.

Weather data included: precipitation, storm duration, average event intensity, 5-, 10-, 15-, 30-, and 60 minute max intensity, and 1-day, 2-day, and 3-day antecedent rainfall

(Supplemental Table 1). Precipitation was measured using unheated rain gauges and FTS tipping bucket rain gauges (Stuntebeck et al., 2008; Rassmussen and Matteson, 2011). Precipitation data were linked to individual runoff events to show the impact of each storm on the runoff. Individual storm events were determined using the criteria of at least 120 minutes of no precipitation before or after the event (Radatz et al., 2012) and total precipitation of 0.01 inches or more. When multiple precipitation events occurred during a single runoff event, precipitation events were combined and associated variables (e.g. average intensity, storm duration) were adjusted accordingly. Likewise, when two or more runoff events occurred during a single precipitation event, the runoff events were combined into a single event. Some runoff events did not have any precipitation associated with them and were classified as missing data. The precipitation gauges did not measure snowfall, so runoff events that were driven by snowmelt were classified as “snowmelt” and do not have associated storm information.

Soil Analysis and Runoff Sampling

Water quantity and quality data were continuously collected at the edge of each field. Runoff events were defined as the time in which rainfall or snowmelt induced runoff began until the runoff ceased (Stuntebeck et al., 2008). Runoff was collected using H or trapezoidal flumes with plywood enclosures and wooden wingwalls in waterways or points of concentrated flow near the fields (Figure 2). Non submersible pressure transducers, along with nitrogen bubbler systems tracked stage within the flumes. Samples were collected through automated time-based ISCO samplers and stored in a refrigerated enclosure (Stuntebeck et al., 2008; Rassmussen and Matteson, 2011). These samples were retrieved within 24 hours of the discharge and sent to an accredited third-party laboratory for analysis, where total P (TP), dissolved P (DP), and particulate P (PP) were measured. Concentrations from the sample were multiplied by the runoff event volume to calculate the event loads. Sampling procedures are detailed in Stuntebeck et al (2008). Routine soil testing was carried out at each site. Soil test phosphorus (STP) was determined using Bray-P1 and Olsen methodology at 0-5 cm and 0-15 cm depths. Average values across the monitoring period were used for each site.

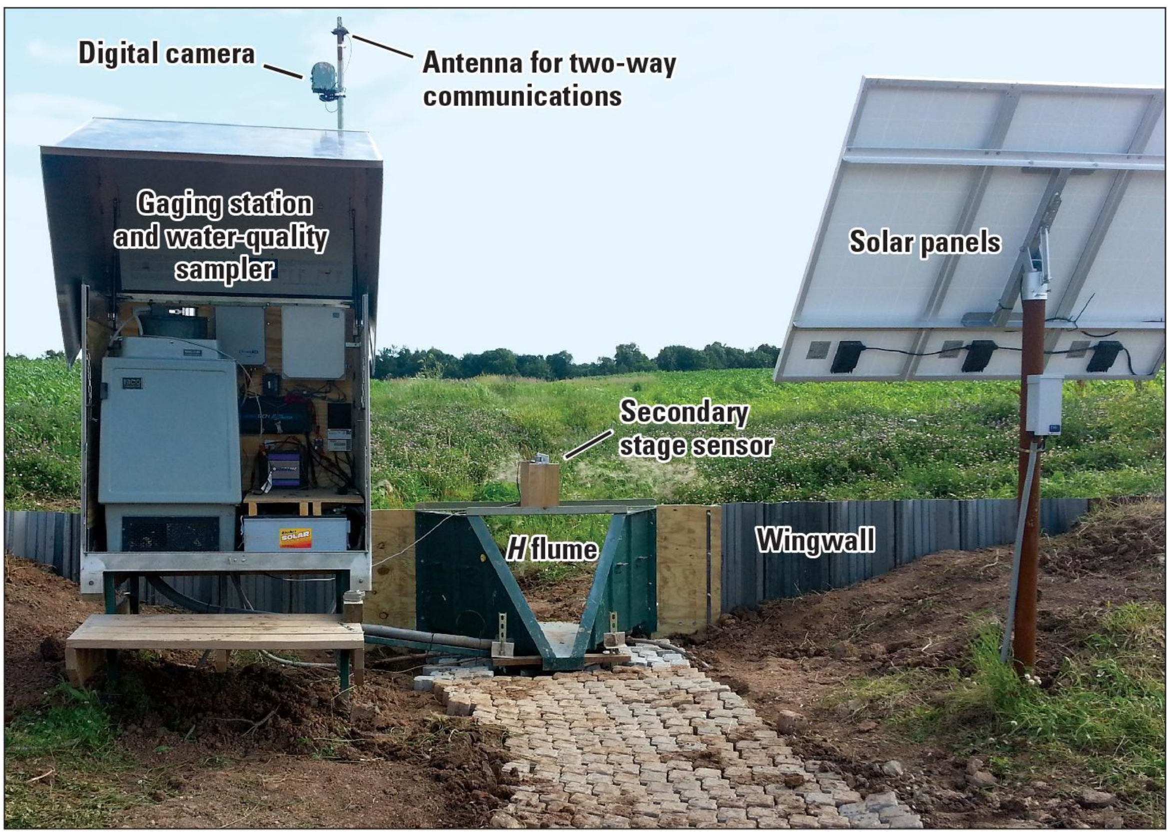

Figure 2. Edge-of-field monitoring station (USGS, 2016).

Statistical Analysis

Data were analyzed using R Studio version 4.0.3 (R Core Team, 2020). Histograms, QQ plots, and residual plots were created to understand the distribution of the data and check for normality. A log-transformation, log(count + 0.0025), was used when TP, DP, TP FWMC, and DP FWMC were not normally distributed. The package 'psych' was used for summary statistics of continuous variables (Revelle W, 2021). The coefficient of variation (CV) was calculated by dividing the standard deviation by the mean. Regression analyses and ANOVA were performed using the 'lm' and 'anova' functions in base 'R' to understand the relationships between the key response variables and independent variables. The 'agricolae' package was used to perform least significant difference tests using the 'lsd.test' function (Mendiburu, 2020). Box and whisker plots with groupings from the lsd test were used to visually compare categorical variables. Table 1 provides descriptions of categorical variables considered in this study. A p-value of ≤ 0.05 was considered statistically significant.

LMM analysis was used to understand the relationships between response and independent variables. The package 'lme4' was used for LMM analysis using the 'lmer' function, which fit with a Gaussian error distribution (Bates et al., 2015). Our model included site and month as random effects. Three models were created to understand what may be influencing P loss. The first model was designed to include the highest number of observations. Hydrologic group, crop, tillage type, surface condition, manure application (if manure was applied coded 0, no manure applied coded 1), STP 0-5cm, STP 0-15cm, and runoff type were all included in the first model as fixed effects. The second model was constructed to understand how the number of days from manure application influences P loss. The same variables from the first model were used, except the binary for manure application was replaced with a continuous variable representing the number of days since manure application. The third model was created to understand how continuous precipitation variables were influencing P loss. Similar to the first model, hydrologic group, crop, tillage type, surface condition, manure application (if manure was applied coded 0, no manure applied coded 1), STP 0-5cm, and STP 0-15cm were in the model. Additionally, soil condition (non-frozen soil coded 0, frozen soil coded 1), precipitation, storm duration, average intensity, 5 minute max intensity, and antecedent rainfall 2 day were included. These variables were chosen under the philosophy described by Oldfield et al. (2019) and Hobbs et al. (2012), where knowledge of biological and soil processes guides the inclusion of factors within the model and model selection.

The square root of the variance inflation factors was used to determine collinearity among the fixed effects. A value of <2 indicates low collinearity. Standardized coefficients were used to compare the effect sizes of the factors. Using the method described in Gelman (2008), standardizing involved subtracting the mean of each variable and dividing it by two standard deviations, leaving a mean of 0 and a standard deviation of 0.5. This allowed comparison between continuous and binary variables to understand their relative effect sizes.

Table 1. Definition and Distribution of Categorical, Independent Variables

Count (n)	Number of sites	Category
Site ID		
49	1	AR1 – Arndt 1
31	1	AR2 – Arndt 2
110	1	BE1-F – Hager Surface
102	1	CH1-F – Peterson Surface
50	1	DO1-F – Herbst Surface
80	1	GO1-F – Schafer Surface
21	1	H3 – Heisner 3
77	1	JF4 - Neubauer
83	1	JF5 - Misna
25	1	KP3 – Koepke 3
49	1	P1 – Pagel 1
39	1	P2 – Pagel 2
57	1	P3 – Pagel 3
77	1	R1 – Riechers 1
58	1	R2 – Riechers 2
69	1	R3 – Reichers 3
32	1	RE1 – Rebout 1
37	1	RE5 – Rebout 5
68	1	RO1-F - Bakken Surface
57	1	ST1-F – Meyer Surface
99	1	WF1 – Mitchell
69	1	WR1-F- Groos Surface
State		
536	7	MN
803	15	WI
Soil type		
69	1	Clay loam
159	2	Loam
31	1	Sandy loam
970	17	Silt loam
110	1	Silty clay loam
Hydrologic Group		
31	1	A
754	11	B
98	2	C
456	8	C/D
Drainage Class		
1028	17	Well drained/ Moderately well drained
311	5	Poorly drained/Somewhat poorly drained
Tiled		
456	8	Yes
883	14	No
Manure		
171	3	No
1168	19	Yes
Soil Condition		
549	22	Frozen
790	22	Non-Frozen

Count (n)	Number of sites	Category
Crop		
237	7	Alfalfa
632	18	Corn
181	3	Corn and alfalfa
12	1	Pea
270	11	Soy
Tillage Type		
794	13	Conventional Tillage (CT)
331	5	No Tillage (NT)
214	4	Reduced Tillage (RT)
Surface Condition		
427	17	Tilled – Crop
407	13	Tilled – No Cover
174	7	Tilled – Residue
62	5	No Till – Crop
135	4	No Till – No Cover
134	5	No Till – Residue
Water year		
91	6	2004
74	7	2005
36	7	2006
42	7	2007
96	6	2008
30	3	2009
26	6	2010
63	7	2011
64	8	2012
108	9	2013
152	10	2014
92	12	2015
144	12	2016
154	13	2017
74	7	2018
93	7	2019
Water Month		
32	15	1 - October
12	5	2 - November
28	20	3 - December
76	21	4 – January
137	21	5 - February
282	22	6 - March
134	18	7 - April
175	20	8 - May
208	22	9 - June
110	18	10 - July
76	21	11 - August
70	16	12 – September
Runoff Type		
230	22	Rainfall on frozen ground
790	22	Rainfall on non-frozen ground
317	22	Snowmelt

RESULTS:

Runoff

Runoff events occurred most frequently from March-June (n=799), with the fall and early winter months (September-December) having the fewest (n=141) runoff events. Runoff occurred year-round, with the most events occurring in March (n=282) and the fewest events occurring in November (n=12) (Figure 3). Event-based runoff across the 125 site years ranged from 0-99.5 mm with a mean value of 0.23 mm (Table 2).

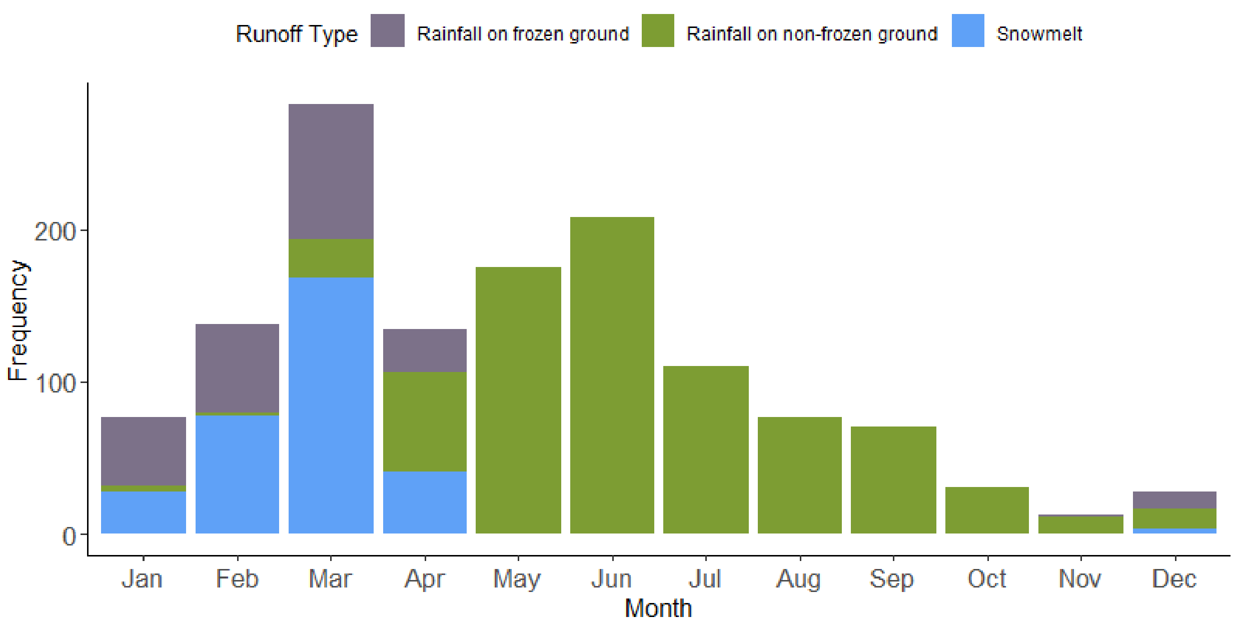

Figure 3. Distribution of runoff events by month (n = 1339). Snowmelt on frozen ground (n = 317), rainfall on frozen ground (n=232), and rainfall on non-frozen ground (n=790).

Total and Dissolved Phosphorus

Event-based TP loss ranged from 0-3.76 kg/ha with a mean value of 0.13 kg/ha and TP FWMC ranged from 0-25.8 mg/L with a mean value of 2.29 mg/L. DP loss ranged from 0-2.91 kg/ha with a mean of 0.07 kg/ha and DP FWMC ranged from 0-21.49 mg/L with a mean of 1.07 mg/L. All of these distributions were skewed to the right, with Table 2 showing the skewness and kurtosis values, as well as other summary statistics for dependent variables.

Linear relationships between DP and TP were moderate and showed DP being driven by snowmelt and rainfall on frozen ground (Figure 4). These relationships were significant and showed a positive correlation; TP and DP loads had a stronger positive linear relationship compared to concentrations ($R^2 = 0.67$, $R^2 = 0.36$, respectively). Within the upper range of observed TP concentrations and loads, TP is almost entirely DP or almost entirely PP. When TP is almost entirely PP, these runoff events are largely driven by rainfall on non-frozen ground. Linear regression for log transformed TP and DP loads and runoff showed the slope (b) to be significantly different from 1 for both TP and DP loads (TP: b= 0.76, confidence interval = +0.73-0.79, $p < 0.05$; DP: b= 0.65, confidence interval = 0.63-0.68, $p < 0.05$). This indicates dilution of TP and DP with increased runoff.

Table 2. Univariate statistics for runoff, sediment, total phosphorus (TP), dissolved phosphorus (DP), and particulate phosphorus (PP) in both loads (kg/ha) and flow-weighted mean concentrations (FWMC) (mg/L).

	Runoff (mm)	**Sediment (kg/ha)**	**TP (kg/ha)**	**DP (kg/ha)**	**PP (kg/ha)**	**Sediment FWMC (mg/L)**	**TP FWMC (mg/L)**	**DP FWMC (mg/L)**	**PP FWMC (mg/L)**
n	1339	1339	1339	1339	1339	1339	1339	1339	1339
Minimum	0	0	0	0	0	0	0	0	0
1st Quartile	0.49	0.31	0.006	0.003	0.002	25	0.75	0.33	0.22
Mean	5.83	38.72	0.13	0.07	0.06	832.07	2.3	1.07	1.23
Median	1.98	1.86	0.02	0.01	0.01	110	1.32	0.62	0.48
3rd Quartile	6.68	12.69	0.12	0.04	0.04	577.64	2.71	1.06	1.23
Maximum	99.5	2631.27	3.76	2.91	2.74	29310.45	25.8	21.49	25.19
Std. Dev	9.84	150.51	0.3	0.2	0.18	2299.46	2.78	1.64	2.23
CV	1.69	3.89	2.31	2.86	16.67	2.76	1.21	1.53	1.81
Skewness	3.57	8.65	5.67	7.21	8.02	6.53	3.34	4.86	4.6
Kurtosis	17.75	103.66	43.81	68.1	90.97	56.82	15.94	34.42	29.86

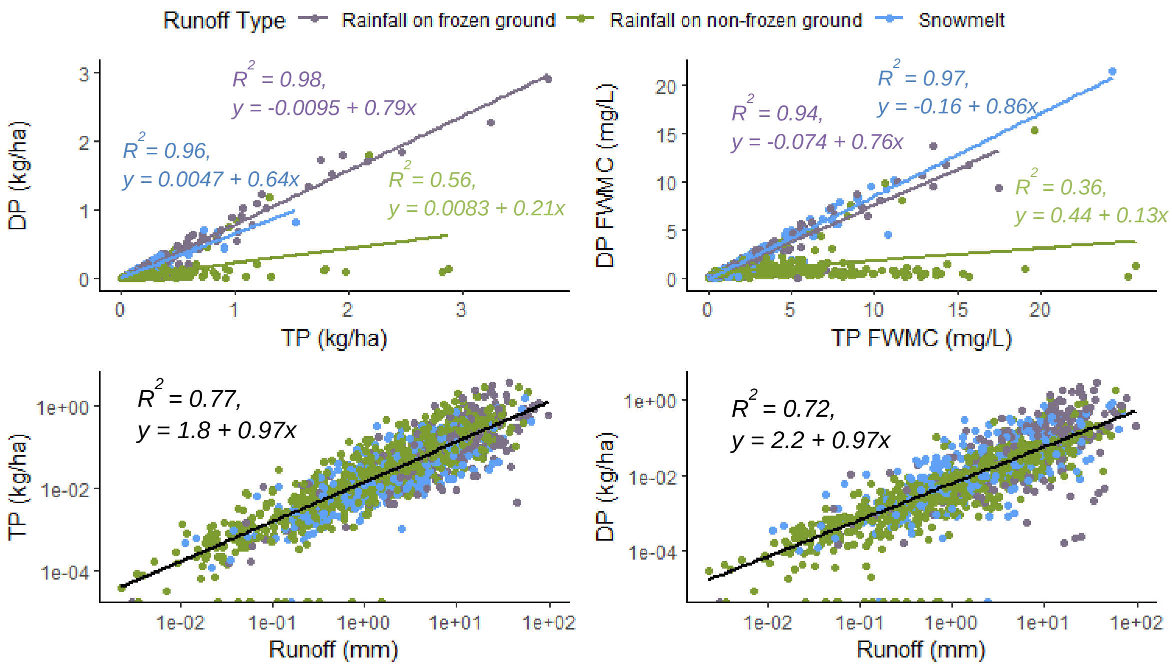

Figure 4. Relationships between total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC) without log transformation (n=1339). Relationships between log transformed total phosphorus load (TP) and dissolved phosphorus load (DP), and runoff. Snowmelt on frozen ground (n = 317), rainfall on frozen ground, (n=232), and rainfall on non-frozen ground (n=790) are shown. Linear regression models and R^2 reported for each figure.

Weather

Weather variables were more significantly correlated with TP loads and concentrations than DP loads and concentrations, however, these relationships did not explain much of the variation (Supplementary Table 2). TP had a significant positive relationship with precipitation, while DP significant negative relationship with precipitation (ranged from 0.46-246 mm with a mean value of 15.9 mm). TP and DP had a significant positive relationship with storm duration (ranged from 0.05-80.77 hrs with a mean value of 6.21 hrs) (Supplementary Table 2). DP was significant and positively correlated to average intensity. TP FWMC had a significant positive relationship with storm duration and significant negative relationship with average intensity. The R^2 of these significant relationships ranged from 0.01 - 0.03 for TP, DP, and TP FWMC. DP FWMC did not have a significant relationship with any of the weather variables.

Runoff event type (rainfall on frozen or non-frozen ground and snowmelt) was an important factor for P loss. Rainfall on frozen ground (41% of the runoff events) resulted in the highest TP and DP (Figure 5). Snowmelt (23% of the runoff events) and rainfall on frozen ground had a similar impact on TP FWMC and DP FWMC. However, rainfall on non-frozen ground (17% of the runoff events) had the lowest DP and DP FWMC, while it had the highest TP FWMC. Rainfall on non-frozen ground had less TP, DP, and DP FWMC, whereas frozen soils had less TP FWMC.

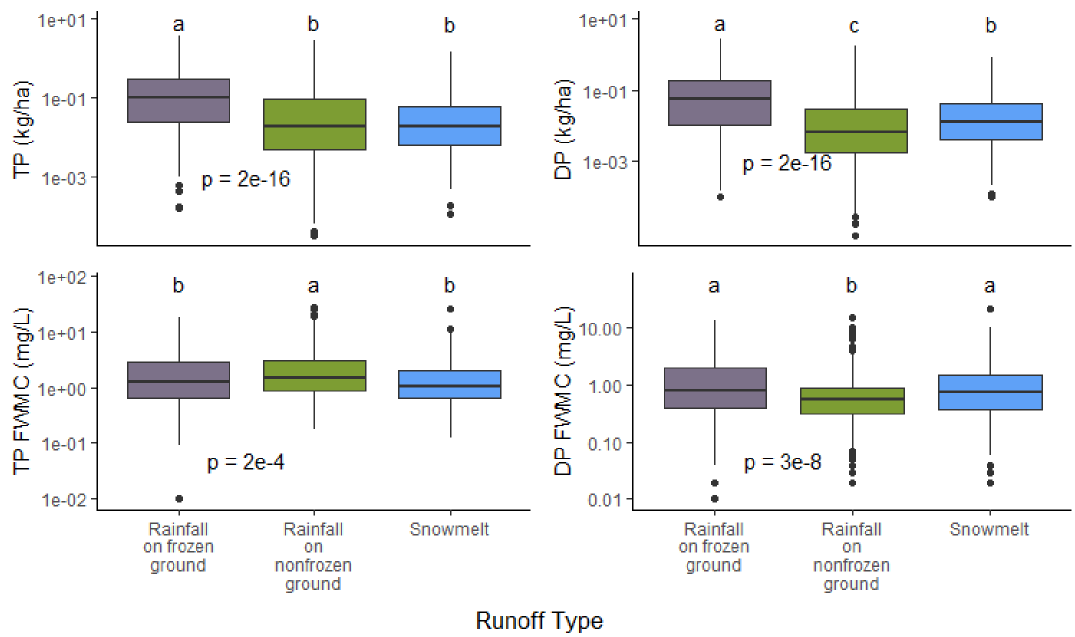

Figure 5. Boxplots of runoff event type (n=1339), and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.

Management

Manure application timing was significant to P loss, but the linear relationships between days since manure application and TP, DP, TP FWMC, and DP FWMC were weak. Nineteen of the 22 sites had at least one manure application during their monitoring period. Of these 19 sites, a large number of manure applications occurred in October and November (Supplemental Figure 4). Linear regression analysis showed TP, DP, TP FWMC, and DP FWMC were significantly related to the number of days since manure application, however R^2 values were low (0.09-0.14) (Supplemental table 3). These linear relationships showed a decrease in P loads and concentrations with time since manure application (Figure 6). DP and DP FWMC were generally higher during snowmelt and rainfall on frozen ground runoff events (Figure 6). Whether or not manure was applied to a site was significant to DP FWMC, with fields that had applied manure with slightly lower DP FWMC compared to those without manure application (Supplemental Figure 1). The number of runoff events since a manure application also had a significant linear relationship with TP, DP, TP FWMC, and DP FWMC, and showed a decrease as more runoff events occurred. However, this linear relationship did not explain much of the variation (R^2 ranged from 0.01-0.05) (Supplemental Table 3).

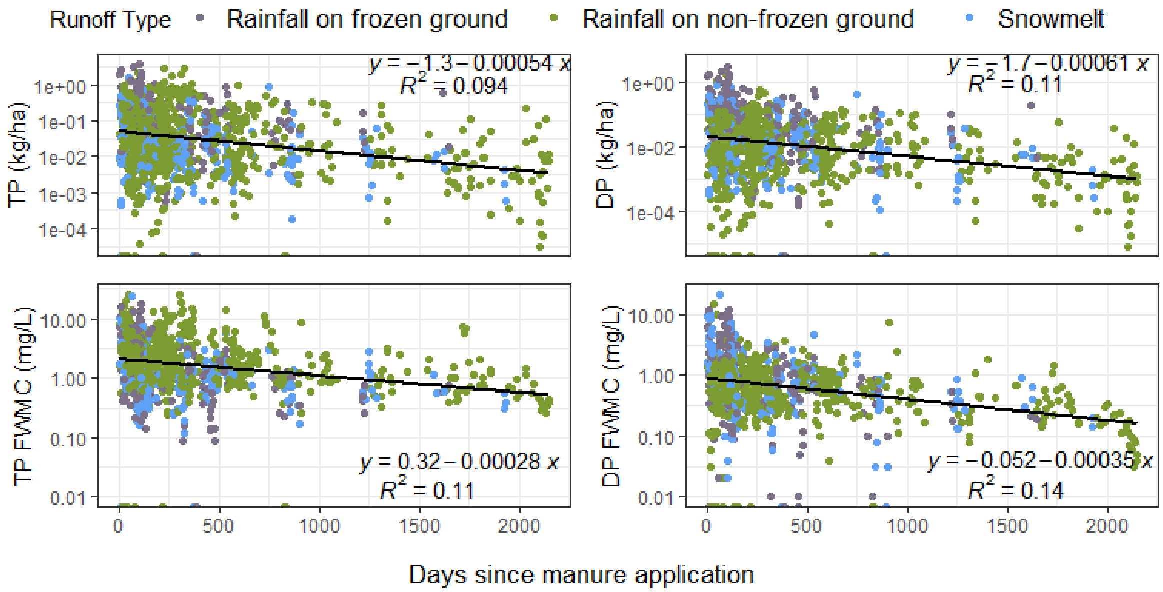

Figure 6. Days since manure application (n= 1062) and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). Linear regression models were run using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale. Linear regression models and R^2 reported for each figure.

Significant differences in TP, DP, TP FWMC and DP FWMC were observed among tillage types (p = 0.03, 2e-13, 5e-5, 2e-16, respectively), where tilled sites had fewer losses than no till. The number of days since tillage did not have a significant linear relationship on TP, DP, or DP FWMC but was significant and negatively correlated with TP FWMC (Supplemental Table 3). TP and TP FWMC losses were statistically lower in CT and RT sites compared to NT (Supplementary Figure 6). Furthermore, TP losses were higher due to rainfall on frozen ground events in NT and RT sites (Figure 7). The least amount of TP loss occurred in RT sites when precipitation occurred on non-frozen ground and in CT sites during snowmelt. TP FWMCs were highest for rainfall on frozen ground in NT sites and were statistically similar to snowmelt in NT sites and rainfall on frozen ground in RT sites. The smallest TP concentrations occurred in CT during frozen conditions (rainfall on frozen ground and snowmelt) and RT sites during rainfall on non-frozen ground. DP losses, both in load and FWMC, were lowest from CT sites, followed by RT, then NT (Supplementary Figure 6). The highest DP loads occurred during rainfall on frozen ground in NT and RT sites. The lowest DP loads occurred in CT sites during rainfall on non-frozen ground. Similar results were seen in DP FWMC, however, high losses during rainfall on frozen ground in RT sites were also statistically similar to snowmelt in NT sites. Likewise, statistically similar losses from CT sites during non-frozen precipitation were observed in RT non-frozen precipitation and CT frozen precipitation. Overall, NT had the most P loss and higher DP and DP FWMC occurred in frozen conditions regardless of tillage practices.

There were significant differences in TP, DP, TP FWMC, DP FWMC among crop types, with Alfalfa (n=237) having the lowest P loss out of all the crops in this study (Supplemental Figure 3). Pea was among the highest P loss out of the crops, but had a small sample size (n=12) compared to the other crops. TP loss was high and statistically similar among corn, corn and alfalfa, and pea. TP FWMC for alfalfa was significantly lower than the other crop types, while all the other crop types had statistically similar concentrations. Statistically similar amounts of DP loss occurred in corn, corn and alfalfa, and soy. DP FWMC losses showed corn and pea with the highest concentrations.

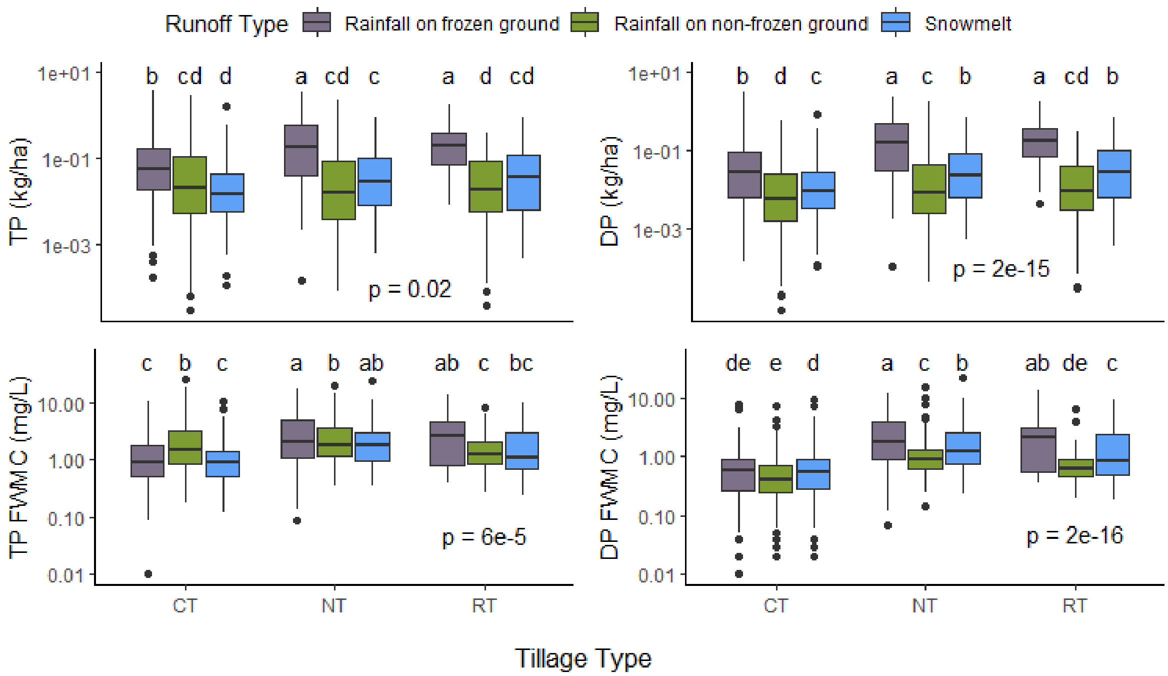

Figure 7. Boxplots of CT (n=794), NT (n=331), or RT (n= 214) and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), or dissolved phosphorus flow-weighted mean concentration (DP FWMC). Snowmelt on frozen ground (n = 317), rainfall on frozen ground (n=232), and rainfall on non-frozen ground (n=790). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.

The surface condition at the time of runoff was statistically significant to TP, DP, TP FWMC, and DP FWMC. Within both tillage conditions considered, P loss was lowest during crop stage (the time between canopy closure of the current crop and a subsequent tillage pass or the harvest of corn silage) (Figure 8). Overall, tilled fields with a crop growing had the lowest P loss and NT with no cover had the highest P loss. A pattern emerged in the no till sites, where no cover had the highest TP, DP, TP FWMC, and DP FWMC, followed by residue, then crop. These differences were statistically significant for TP and DP. For TP FWMC, NT residue and NT crop were statistically similar. DP FWMC showed no cover and residue with statistically similar amounts of loss. The same pattern in NT sites can be seen in TP and TP FWMC for tilled sites. TP losses were not statistically different between no cover and residue in tilled conditions. TP FWMC showed crop and residue to be statistically similar in tilled conditions. DP loads and concentrations in tilled sites had a unique pattern where crop remained the lowest grouping, followed by no cover, then residue with the highest amount of loss. These were all statistically different for DP FWMC. DP losses were statistically similar in no cover and residue conditions.

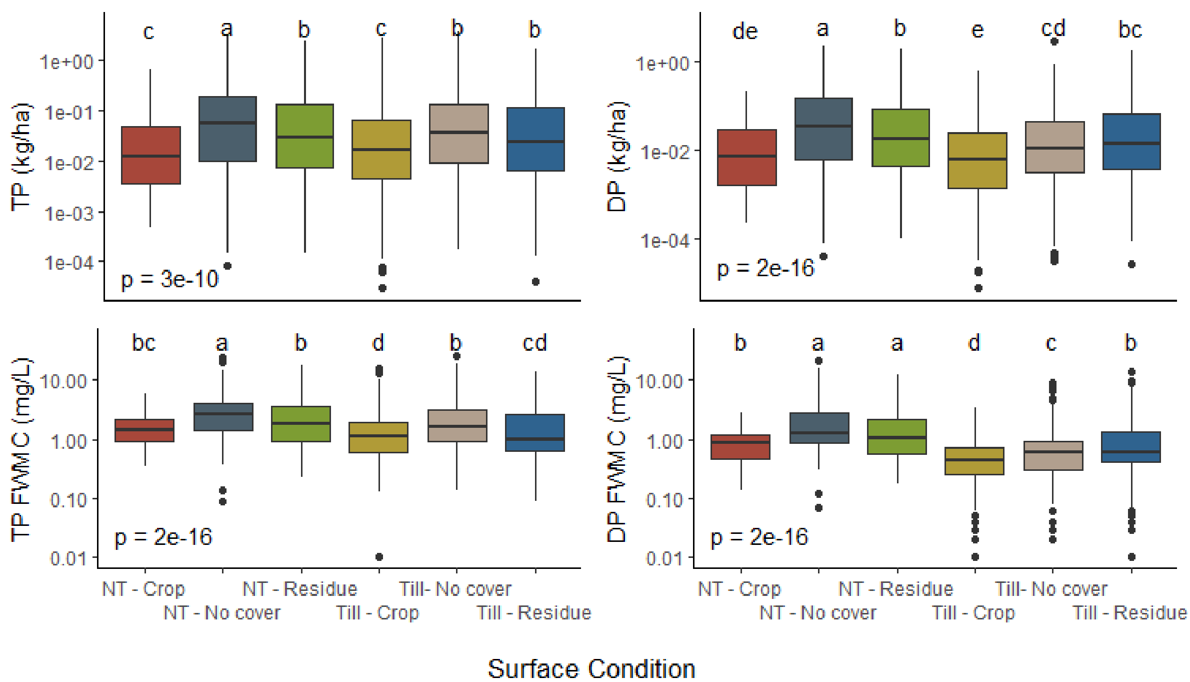

Figure 8. Boxplots of surface condition (n=1339), in both tilled and no till treatments, and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.

Soil Test Phosphorus

High amounts of STP were found in both the WI and MN sites. STP at the 0-5cm depth ranged from 32 - 143 ppm with a median value of 71.98 ppm. At the 0-15cm depth ranged from 18-85 ppm with a median value of 47.76 ppm. All of the STP measurements for Wisconsin in the 0-5cm depth were in the “excessively high” range based on agronomic requirements (Laboski and Peters, 2012). 46% of the 0-15cm depth for Wisconsin were in the “excessively high” range, 37% were in the “high” range, and 12.3% in the “optimum” range. All of the STP measurements for Minnesota were in the “very high” range (Kaiser and Pagilari, 2018). The largest STP values occurred in NT and RT sites (Supplementary Figure 7). TP FWMC and DP FWMC had a significant positive relationship with STP at both depths. There was a significant positive relationship between TP and DP and STP 0-5 cm, but the relationships were weak (Supplemental Table 2). The 0-15cm depth had a significant positive relationship with DP.

Linear Mixed Model

Linear mixed models (LMM) were developed for TP, DP, TP FWMC, and DP FWMC to understand how management, soil condition, and weather influence P loss. Three models were created for each of the response variables- the first designed to include the most data (n=1318), the second to focus on manure application timing (n=1040), and the third to include continuous weather data (n=973). The intercept for each model represents a baseline condition in which the other factors are compared against. Standardized coefficients are used to compare effect sizes and how those factors influence TP, DP, TP FWMC, and DP FWMC. Large absolute values of standardized coefficients show that there is a larger effect on the response variable compared to the other factors considered. The negative coefficient means a decrease in the response variable, whereas a positive coefficient means an increase in the response variable.

Total Phosphorus Load

The LMM results showed that the hydrologic group and rainfall on frozen ground were important factors influencing TP loss across all models, with individual models identifying other factors with a large effect on TP. Model one had the intercept, hydrologic group B, hydrologic group C/D, alfalfa, no cover, residue, and rainfall on frozen ground as significant factors to TP (Table 3). When the intercept is significant, it means that the baseline factors are significant to TP loss. In model one, the intercept represented a site in hydrologic group A, planted with corn with an active crop growing, in non-frozen conditions. The different hydrologic groups had some of the largest absolute values of the standardized coefficients, meaning they had a larger effect on TP compared to other variables, even when nonsignificant, based on this model. For example, hydrologic group B had a standardized coefficient of -0.631 ±0.239, whereas the no cover surface condition had a standardized coefficient of 0.177 ± 0.056 (Table 3). This showed that no cover had about three times less of an effect on TP than hydrologic group B. Model two had the intercept, hydrologic group B, hydrologic group C/D, number of days since manure application, and rainfall on frozen ground as significant factors to TP (Table 4). The hydrologic groups also had the highest standardized coefficients for this model. Model three showed TP and the intercept, hydrologic group B, hydrologic group C/D, alfalfa, no cover, residue, frozen soil conditions, precipitation, 5 minute max intensity, and antecedent two day rainfall to be significant (Table 5). Rainfall on frozen ground had the largest effect in this model. Across all three models, the largest effects on TP appeared with hydrologic group B and C/D and rainfall on frozen ground.

Dissolved Phosphorus Load

The most influential factors to DP loss were NT and rainfall on frozen ground in all three models, where hydrologic group B and C/D, surface condition, manure application timing, STP at the 0-5cm depth, and weather conditions had a large effect in specific models. Rainfall on frozen ground had the largest effect on DP loads in models one and three, and the third highest standardized coefficient behind NT in model two, showing its large influence on DP loss (Tables 3-5). Hydrologic group B and C/D, no cover, and rainfall on frozen ground were significant in models one and two. Residue was significant to models one and three, but with a smaller effect size than several other factors considered. Models two and three showed STP 0-5cm to be significant and with a large effect size. In model one, STP 0-5cm has one of the larger effect sizes as well. The second model had days since manure application as significant and with a moderate effect size. The third model also showed DP and precipitation, five minute max intensity, and two day antecedent rainfall to be significant. Among these weather variables, DP loss was most effected by precipitation. Taken together, these results show that DP loss is largely influenced by the tillage and runoff type.

Table 3. Output of linear mixed model one on TP FWMC, DP FWMC, TP, and DP (n=1318). Marginal R^2, describes variance from the fixed factors alone, and Conditional R^2 describes variance from both fixed and random factors. Site and month were random factors. Manure application was coded as binary (0= manure applied, 1= no manure applied). Standardized coefficients allow for direct comparison between each variable. Intercept represents a site in hydrologic group A, planted with corn with an active crop growing, in non-frozen conditions. Bolded values represent $p \leq 0.05$. Italicized values represent $p \leq 0.1$.

Variable	TP		DP		TP FWMC		DP FWMC	
	Unstandardized coefficient	Standardized coefficient	Unstandardized coefficient	Standardized coefficient	Unstandardized coefficient	Standardized Coefficient	Unstandardized coefficient	Standardized coefficient
Intercept	**-1.120±0.279**	**-1.08 ± 0.373**	**-1.790±0.244**	**-1.88 ± 0.0328**	**0.49 ± 0.2195**	**0.635 ±0.294**	-0.231 ±0.2670	-0.21 ± 0.36
Hydrologic group B	**-0.631±0.239**	**-0.631 ±0.239**	*-0.401±0.211*	*-0.401 ± 0.211*	**-0.423 ± 0.1862**	**-0.423 ± 0.186**	-0.229 ±0.229	-0.229 ± 0.229
Hydrologic group C	-0.474±0.484	-0.474 ± 0.484	-0.404±0.4280	-0.404 ± 0.428	-0.425 ± 0.3816	-0.425 ± 0.381	-0.255 ±0.473	-0.255 ± 0.229
Hydrologic group C/D	**-0.667±0.232**	**-0.667 ± 0.232**	**-0.443±0.2050**	**-0.443 ± 0.205**	**-0.508 ± 0.1812**	**-0.508 ± 0.181**	-0.365 ±0.223	-0.364 ± 0.223
Alfalfa	**-0.324±0.0724**	**-0.324 ± 0.072**	**-0.143±0.0624**	**-0.143 ± 0.062**	**-0.234 ± 0.05**	**-0.234 ± 0.05**	-0.082 ±0.052	-0.082 ± 0.052
Corn and alfalfa	0.197±0.227	0.197 ± 0.227	0.208±0.2010	0.208 ± 0.201	0.0862 ± 0.1807	0.086 ± 0.181	0.136 ±0.225	0.136 ± 0.225
Pea	-0.054±0.197	-0.054 ± 0.197	*0.328±0.17*	*0.328 ± 0.17*	-0.177 ± 0.1341	-0.177 ± 0.134	*0.265 ±0.139*	*0.265 ± 0.139*
Soy	0.008±0.0502	0.008 ± 0.05	0.022±0.0434	0.022 ± 0.043	**-0.159 ± 0.0343**	**-0.159 ± 0.034**	**-0.120 ±0.0355**	**-0.124 ± 0.036**
No Till	0.079±0.223	0.079 ± 0.223	**0.474±0.197**	**0.474 ± 0.197**	0.129 ± 0.1742	0.129 ± 0.174	**0.576 ±0.214**	**0.576 ± 0.214**
Reduced Tillage	-0.095±0.3	-0.095 ± 0.3	0.321±0.265	0.321 ± 0.265	-0.131 ± 0.2358	-0.131 ± 0.236	0.227 ±0.292	0.227 ± 0.292
No Cover	**0.177±0.056**	**0.177 ± 0.056**	**0.109±0.0468**	**0.109 ± 0.045**	**0.219 ± 0.0389**	**0.219 ± 0.039**	**0.150 ±0.0392**	**0.15 ± 0.039**
Residue	**0.159±0.065**	**0.159 ± 0.065**	**0.149±0.0546**	**0.149 ± 0.055**	**0.1823 ± 0.045**	**0.182 ± 0.045**	**0.183 ±0.0455**	**0.183 ± 0.046**
Manure application	0.064±0.265	0.064 ± 0.265	0.172±0.234	0.172 ± 0.234	-0.0973 ± 0.2098	-0.097 ± 0.21	-0.042 ±0.261	-0.042 ± 0.261
STP 0-15cm	0.0044±0.0042	0.177 ± 0.17	0.005±0.0038	0.216 ± 0.151	0.006 ± 0.0034	0.223 ± 0.135	*0.008 ±0.0042*	*0.333 ± 0.168*
STP 0-5cm	-0.0024±0.0032	-0.171 ± 0.225	*-0.005±0.0028*	*-0.347 ±0.1991*	-0.002 ± 0.0025	-0.115 ± 0.177	-0.005 ±0.0031	-0.367 ± 0.219
Snowmelt	-0.008±0.0702	-0.008 ± 0.07	*0.142±0.0546*	*0.142 ±0.055*	-0.036 ± 0.051	-0.036 ± 0.05	**0.144 ±0.048**	**0.144 ± 0.048**
Rainfall on frozen ground	**0.528±0.0735**	**0.528 ± 0.074**	*0.606±0.0579*	*0.606 ±0.058*	-0.024 ± 0.0531	-0.024 ± 0.05	**0.093 ±0.0504**	**0.093 ± 0.05**
Marginal R^2	0.17		0.23		0.17		0.25	
Conditional R^2	0.27		0.30		0.32		0.38	

Table 4. Output of linear mixed model two on TP FWMC, DP FWMC, TP, and DP (n=1040). Marginal R^2, describes variance from the fixed factors alone, and Conditional R^2, describes variance from both fixed and random factors, reported for each response variable. Site and month were random factors. Standardized coefficients allow for direct comparison between each variable. Intercept represents a site in hydrologic group A, planted with corn with an active crop growing, in nonfrozen conditions. Bolded values represent $p \leq 0.05$. Italicized values represent $p \leq 0.1$.

Variable	TP		DP		TP FWMC		DP FWMC	
	Unstandardized coefficient	Standardized Coefficient	Unstandardized coefficient	Standardized coefficient	Unstandardized coefficient	Standardized coefficient	Unstandardized coefficient	Standardized coefficient
Intercept	**-0.7760±0.22**	**-0.97±0.18**	**-1.3700±0.22**	**-1.722±0.173**	**0.5810 ±0.131**	**0.579±0.113**	-0.0546±0.22	-0.265±0.174
Hydrologic group B	**-0.6930±0.18**	**-0.693±0.178**	**-0.4170±0.18**	**-0.417±0.179**	**-0.4790 ±0.102**	**-0.479±0.102**	-0.2320±0.18	-0.232±0.183
Hydrologic group C	-0.4200±0.37	-0.42±0.369	-0.3010±0.38	-0.301±0.378	-0.3130 ±0.2	-0.313±0.2	-0.0499±0.39	-0.05±0.394
Hydrologic group C/D	**-0.6150±0.17**	**-0.615±0.174**	**-0.4200±0.17**	**-0.42±0.174**	**-0.4620 ±0.1**	**-0.462±0.1**	*-0.3580±0.18*	*-0.128±0.179*
Alfalfa	-0.1150±0.08	-0.115±0.077	-0.0478±0.07	-0.048±0.069	-0.0638 ±0.051	-0.064±0.051	-0.0359±0.06	-0.036±0.061
Corn and alfalfa	0.1780±0.16	0.178±0.161	0.1890±0..17	0.189±0.168	0.0906 ±0.0843	0.091±0.084	0.1280±0.18	0.128±0.176
Pea	0.0080±0.19	0.008±0.192	*0.3050±0.17*	*0.305±0.166*	-0.0830 ±0.136	-0.083±0.136	*0.2580±0.15*	*0.258±0.145*
Soy	-0.0661±0.06	-0.0661±0.057	-0.0385±0.05	-0.039±0.049	**-0.2130 ±0.041**	**-0.213±0.041**	**-0.1470±0.04**	**-0.147±0.043**
No Till	0.2380±0.17	0.238±0.171	**0.6570±0.17**	**0.657±0.171**	**0.2700 ±0.0962**	**0.27±0.096**	**0.7640±0.18**	**0.764±0.175**
Reduced Tillage	-0.2480±0.25	-0.248±0.245	0.1730±0.25	0.173±0.25	**-0.3580 ±0.133**	**-0.358±0.133**	-0.0479±0.26	-0.048±0.26
No Cover	*0.1140±0.06*	*0.114±0.063*	*0.1030±0.05*	*0.103±0.053*	**0.1410 ±0.0454**	**0.141±0.045**	**0.1210±0.05**	**0.121±0.045**
Residue	0.0626±0.07	0.063±0.074	0.0961±0.06	0.096±0.063	*0.1030 ±0.0353*	*0.103±0.054*	**0.1390±0.05**	**0.139±0.054**
Days since manure application	**-0.0003±0.0001**	**-0.3±0.057**	**-0.0002±0.0001**	**-0.24±0.049**	**-0.0002 ±0.00004**	**-0.196±0.039**	**-0.0002±4**	**-0.201±0.043**
STP 0-15cm	0.0016±0.003	0.069±0.134	0.0037±0.003	0.157±0.137	*0.0032 ±0.0017*	*0.136±0.073*	*0.0069±0.003*	*0.293±0.143*
STP 0-5cm	-0.0020±0.002	-0.154±0.187	**-0.0058±0.003**	**-0.552±0.190**	-0.0010 ±0.001	-0.077±0.103	**-0.0063±0.003**	**-0.488±0.197**
Snowmelt	-0.0818±0.08	-0.082±0.081	0.0981±0.07	0.098±0.066	-0.0558 ±0.060	-0.056±0.03	**0.1470±0.06**	**0.147±0.055**
Rainfall on frozen ground	**0.4840±0.09**	**0.484±0.085**	**0.5870±0.07**	**0.587±0.07**	-0.0469 ±0.063	-0.047±0.063	0.0837±0.06	0.084±0.059
Marginal R^2	0.21		0.29		0.21		0.32	
Conditional R^2	0.30		0.36		0.31		0.39	

Table 5. Output of linear mixed model three on TP FWMC, DP FWMC, TP, and DP (n=973). Marginal R^2 describes variance from the fixed factors alone, and Conditional R^2 describes variance from both fixed and random factors, reported for each response variable. Site and month were random factors. Manure application was coded as binary (0= manure applied, 1= no manure applied); Soil condition was coded as binary (0= non-frozen soi;; 1= frozen soil). Standardized coefficients allow for direct comparison between each variable. Intercept represents a site in hydrologic group A, planted with corn with an active crop growing, in frozen conditions. Bolded values represent $p \leq 0.05$. Italicized values represent $p \leq 0.1$.

Variable	TP		DP		TP FWMC		DP FWMC	
	Unstandardized coefficient	Standardized coefficient	Unstandardized coefficient	Standardized coefficient	Unstandardized coefficient	Standardized Coefficient	Unstandardized coefficient	Standardized coefficient
Intercept	**-0.964±0.27**	**-0.39 ± 0.347**	**-1.502±0.23**	**-1.23 ±0.299**	**0.442±0.207**	**0.48 ± 0.207**	-0.098±0.27	-0.08 ± 0271
Hydrologic group B	**-0.611±0.22**	**-0.611 ± 0.221**	*-0.369±0.19*	*-0.369 ±0.192*	**-0.418±0.174**	**-0.418 ± 0.174**	-0.218±0.23	-0.218 ± 0.229
Hydrologic group C	-0.365±0.45	-0.365 ± 0.451	-0.317±0.39	-0.314 ±0.39	-0.321±0.36	-0.321 ± 0.0358	-0.13±0.48	-0.128 ± 0.475
Hydrologic group C/D	**-0.620±0.22**	**-0.62 ± 0.215**	*-0.359±0.19*	*-0.36 ±0.186*	**-0.53±0.17**	**-0.53 ± 0.169**	-0.352±0.22	-0.353 ± 0.222
Alfalfa	**-0.376±0.08**	**-0.375 ± 0.077**	-0.126±0.07	-0.132 ±0.066	**-0.337±0.053**	**-0.337 ± 0.053**	-0.091±0.06	-0.093 ± 0.057
Corn and alfalfa	0.247±0.21	0.246 ± 0.21	0.255±0.18	0.255 ±0.183	0.179±0.17	0.179 ± 0.169	0.23±0.23	0.229 ± 0.227
Pea	-0.269±0.19	-0.269 ± 0.188	0.139±0.16	0.139 ±0.161	*-0.237±0.13*	*-0.237 ± 0.128*	0.2±0.14	0.2 ± 0.137
Soy	-0.059±0.05	-0.059 ± 0.052	-0.039±0.05	-0.038 ±0.044	**-0.193±0.0356**	**-0.193 ± 0.035**	**-0.161±0.04**	**-0.16 ± 0.038**
No Till	0.047±0.21	0.047 ± 0.207	**0.551±0.18**	**0.578 ±0.179**	0.000005±0.16	0.00008 ± 0.163	**0.58±0.21**	**0.578 ± 0.214**
Reduced Tillage	-0.273±0.28	-0.273 ± 0.278	0.257±0.24	0.255 ±0.24	-0.317±0.22	-0.317 ± 0.22	0.12±0.3	0.119 ± 0.292
No Cover	**0.187±0.06**	**0.187 ± 0.06**	*0.098±0.05*	*0.094 ±0.049*	**0.221±0.04**	**0.221 ± 0.04**	**0.109±0.04**	**0.108 ± 0.042**
Residue	**0.156±0.07**	**0.156 ± 0.071**	**0.155±0.06**	**0.153 ±0.06**	**0.216±0.048**	**0.216 ± 0.048**	**0.205±0.05**	**0.204 ± 0.051**
Manure application	0.124±0.24	0.124 ± 0.244	0.266±0.24	0.265 ±0.211	-0.145±0.2	-0.145 ± 0.195	-0.08±0.26	-0.08 ± 0.262
Nonfrozen soil	**-0.762±0.08**	**-0.762 ± 0.078**	**-0.846±0.06**	**-0.844 ±0.064**	0.083±0.054	0.083±0.054	*-0.095±0.06*	*-0.095 ± 0.055*
STP 0-15cm	0.006±0.004	0.240 ± 0.157	*0.006±0.003*	*0.252 ±0.136*	**0.0079±0.0032**	**0.0079±0.0032**	**0.01±0.004**	**0.01 ± 0.004**
STP 0-5cm	-0.003±0.003	-0.231 ± 0.207	**-0.006±0.003**	**-0.435 ±0.179**	-0.002±0.0024	-0.002±0.0024	*-0.006±0.003*	*-0.006 ± 0.003*
Precipitation	**0.011±0.001**	**0.46 ± 0.057**	**0.01±0.001**	**0.441 ±0.049**	-0.0003 ±0.000	-0.0003 ±0.000	-0.0014±0.001	0.06 ± 0.041
Storm duration	0.004±0.004	0.053 ± 0.049	0.005±0.003	0.061 ±0.042	-0.004±0.0026	-0.047 ± 0.033	0.002±0.003	-0.018 ± 0.035
Average Intensity	-0.082±0.07	-0.058 ± 0.05	-0.052±0.06	-0.035 ±0.043	-0.061±0.049	-0.043 ± 0.034	-0.012±0.05	-0.008 ± 0.036
5 Min Max Intensity	**0.086±0.02**	**0.296 ± 0.063**	**0.034±0.02**	**0.115 ±0.051**	**0.048±0.012**	**0.167 ± 0.043**	0.003±0.01	-0.012 ± 0.045
Antecedent Rainfall 2 Day	**0.118±0.03**	**0.166 ± 0.039**	**0.111±0.02**	**0.152 ±0.034**	-0.028±0.019	-0.04 ± 0.03	-0.011±0.02	-0.016 ± 0.028
Marginal R^2	0.33		0.38		0.26		0.29	
Conditional R^2	0.42		0.45		0.39		0.44	

Total Phosphorus Flow-Weighted Mean Concentration

LMM results for TP FWMC showed that hydrologic group B and C/D and surface condition, particularly no cover, were important factors for all the models, while other factors had moderate effect sizes (Table 3-5). The hydrologic group had the largest standardized coefficients in all of the models. The first and third models showed the intercept, alfalfa, soy, and residue to be significant to TP FWMC. Alfalfa and soy decreased TP concentrations when compared against baseline conditions. Residue's effect size showed an increase in TP concentrations when compared to the baseline. The second model showed NT, RT, and the number of days since manure application to be significant factors to TP FWMC. These factors had a moderate effect on TP concentrations, with RT and days since manure application showing a decline in concentrations. The third model showed the intercept, residue, STP 0-15cm, precipitation, and five minute max intensity to be significant to TP FWMC. While not significant in model 3, RT had a large effect on TP FWMC compared to other factors.

Dissolved Phosphorus Flow-Weighted Mean Concentration

LMM results for DP FWMC showed that NT, soy, and surface condition were significant factors for DP FWMC, while STP and frozen conditions also influenced DP concentrations in particular models. NT had the largest effect on DP FWMC across all the models (Table 3-5). The first and second models had snowmelt as a significant factor with a moderate effect size. The second model had days since manure application and STP 0-5cm as significant. STP 0-5cm had the second largest effect size on DP FWMC in model two, behind NT. The third model showed STP 0-5cm, and STP 0-15cm to be significant to DP

FWMC, however, the effect sizes were small compared to other factors considered. These results show that NT, frozen conditions, and STP 0-5cm are all influential to DP FWMC loss.

Model Visualization

After developing the models, *a priori* factors and those with large effect sizes were chosen to visualize their relationships with response variables. Since there is a large degree of variability in this dataset, these model results indicate which factors have the strongest influence on P loss. TP and DP FWMC were strongly influenced by tillage and surface condition in model two. Likewise, we were interested in how multiple factors influence TP and DP concentrations in the days after manure application (Figure 9). TP and DP loads in model three were largely affected by rainfall on frozen ground, TP was largely affected by reduced tillage, and DP was largely affected by no till. Evaluating how these loads changed under frozen and nonfrozen conditions, tillage, the different surface conditions as precipitation increased was of interest (Figure 10 and 11). Exploring these relationships provided a deeper understanding of how multiple factors influence TP, DP, TP FWMC, and DP FWMC.

TP FWMC and DP FWMC were strongly influenced by tillage and surface conditions. Figure 8 shows that NT conditions had higher TP FWMC and DP FWMC in comparison to CT and RT. For TP FWMC, CT then had the next highest concentrations, followed by RT. DP FWMC showed NT followed by CT and RT with similar amounts of DP concentration. This implies that the particulate portion of TP is highest in CT, followed by RT, then NT. In all tillage conditions, soil without cover had the highest TP FWMC, followed by residue. The lowest TP FWMC was seen in the crop condition. The crop stage for all of these conditions showed reduced DP FWMC, whereas no cover and residue had very similar concentrations. TP and DP FWMC decreased slightly with days since manure application. These lines represent the effect of tillage and surface condition on TP and DP FWMC as the number of days since manure application increases.

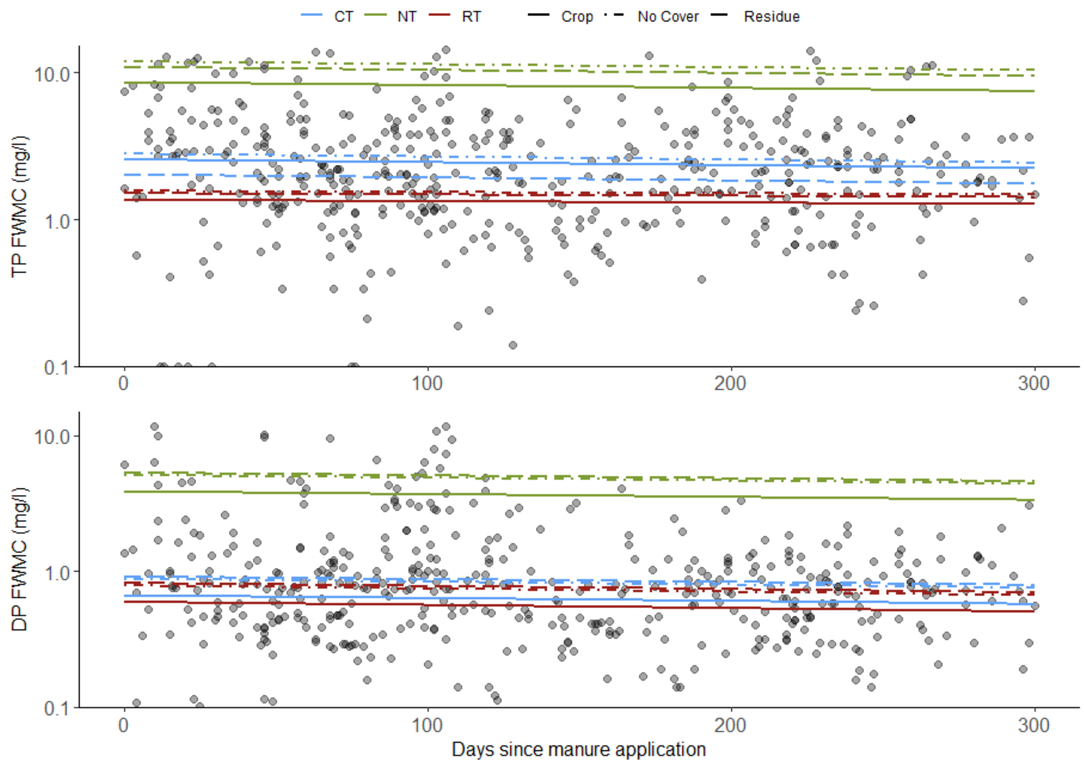

Figure 9. Model two results on TP FWMC and DP FWMC over the number of days since manure application. Results use log transformed TP and DP, and are back-transformed for visualization. Lines represent the different tillage and surface conditions. Lines are plotted on top of the observations from the dataset.

Models results show TP and DP loads were strongly affected by precipitation, tillage, and frozen soil conditions. TP and DP loads increase in frozen conditions compared to non-frozen and that NT sites had the highest losses (Figure 10). Differences in frozen and non-frozen conditions were stark, with frozen conditions having around twice the amount of loss than non-frozen, given the same amount of precipitation, in all tillage conditions. The highest TP and DP loss in both frozen and non-frozen conditions occurred in NT sites. For TP, this was closely followed by CT, then RT. DP had the reverse occur, where RT had more loss than CT. There were larger differences between the three tillage conditions in DP compared to TP.

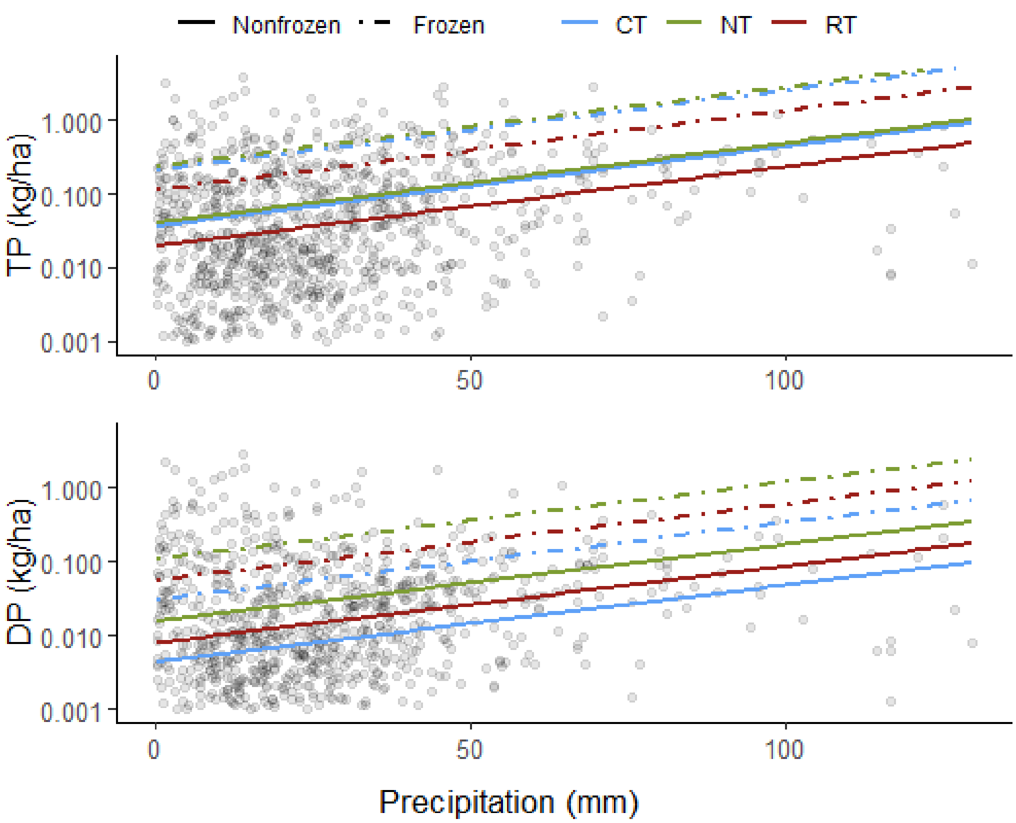

Figure 10. Model three results on TP and DP and precipitation. Model results use log transformed TP and DP, and are back-transformed for visualization. Lines represent the different tillage conditions and whether the event occurred in frozen or non-frozen conditions. Lines are plotted on top of the observations from the dataset, represented by shaded dots. Darker shades are where points are clustered together.

TP and DP loads were also influenced by the surface condition, for this reason we modeled the effects of surface condition and tillage on TP and DP as precipitation increased. TP and DP loads in model 3 were highest in NT sites, and lowest during the crop stage regardless of tillage (Figure 11). TP loads were highest in NT closely followed by CT in all surface conditions. TP loads were highest during no cover conditions, followed by residue, then crop. TP loads were the smallest in RT, and even the crop stage of CT and NT had more TP loss than the no cover stage of RT - the surface condition that showed the highest amount of TP loss. For DP loads, residue had the highest amount of DP loss regardless of tillage. This was followed by no cover then crop. Contrasting with TP, DP showed RT with more loss than CT. In this model, there was less of a difference between the tillage conditions for DP compared to TP, but RT and CT were more similar than NT.

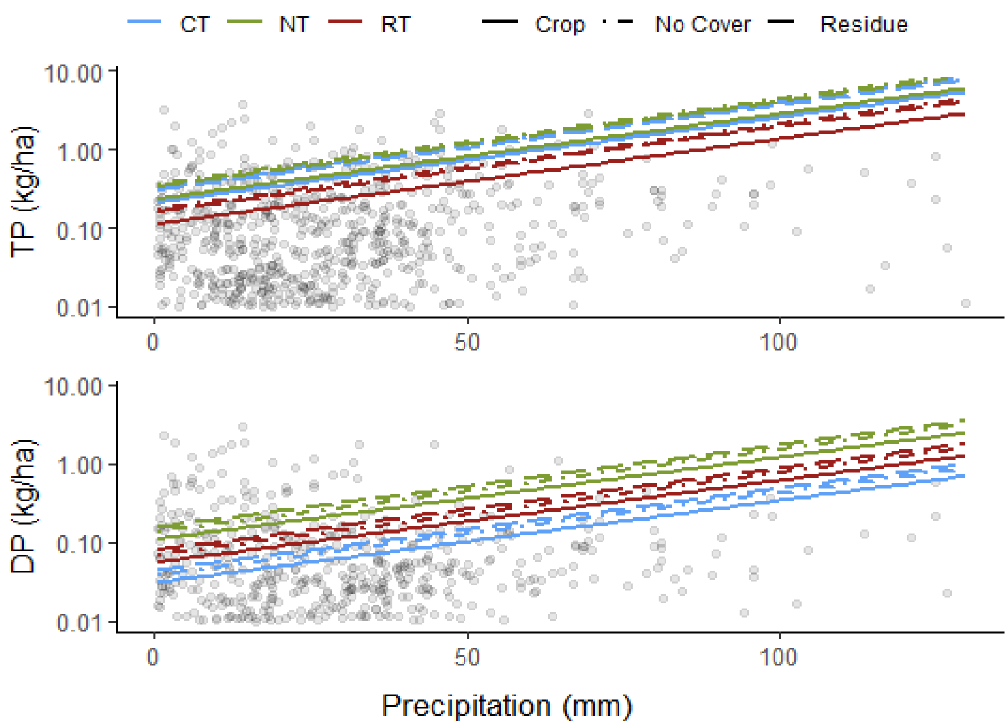

Figure 11. Model three results on TP and DP and precipitation. Model results use log transformed TP and DP, but are back-transformed for visualization. Lines represent the different tillage and surface conditions. Lines are plotted on top of the observations from the dataset, represented by shaded dots. Darker shades are where points are clustered together.

DISCUSSION:

Precipitation and snowmelt lead to runoff and play a large role in loads of nutrients exported from the field. There was a divide between DP and TP in this dataset, where TP and TP FWMC losses were largely during non-frozen soil conditions, and DP and DP FWMC losses were primarily during frozen soil conditions (Figure 3). This aligns with previous literature that describes an increase in DP load and concentration due to snowmelt and rainfall on frozen ground runoff (Li et al., 2011; Hansen et al., 2000; Panuska et al., 2008). Findings from Hoffman et al., (2019) found that TP loss was primarily driven by rainfall on non-frozen ground, and DP made up 74% and 85% of TP during snow and rainfall on frozen ground runoff events, respectively. They attributed this to a lack of infiltration and soil particle mobilization. Similarly, higher amounts of DP and DP FWMC soon after manure application (Figure 4) could be due to a lack of infiltration during frozen conditions (Stock et al., 2019). However, Hoffman et al., ultimately suggest that volume of runoff, not timing of manure, was the most important factor when assessing nutrient loss (Liu et al., 2013b). Model results show that rainfall on frozen ground had a large effect on increasing loads in this dataset, while snowmelt was a large factor in increasing concentrations (Tables 3-4). Similar findings were seen by Liu et al., 2014.

This study provides further information on the impact of manure application timing on P loss on an event basis. The number of days since manure application was significant for TP, DP, TP FWMC, and DP FWMC. Previous studies have shown that P losses increase when rainfall or snowmelt occurs soon after manure applications (Komiskey et al., 2011; Vadas et al., 2011; Klausner et al., 1976). In particular, winter manure applications have been shown to increase DP (Cherobim et al., 2017, Vadas et al., 2019). These studies indicate that increasing the timing between manure applications and precipitation or snowmelt can help reduce P runoff. Our results show that high amounts of P load and concentration can occur close to a manure application, and that P loss declines the farther away from an application (Figure 5). However, the weak relationship between P and days since manure application signifies that other factors are necessary for explaining P loss. This dataset had a limited number of events that occurred within the 0-10 day period after a manure application (n=23), which is the time period the Runoff Risk Advisory Forecast analyzes manure application risk. Of these, 15 runoff events occurred in February and March, when snowmelt and precipitation begin to increase after the winter period. This is also a period in which Wisconsin Department of Natural Resources restricts manure spreading (NR 243). Avoiding manure application during this high-risk period could be one way to reduce surface P runoff.

Model 2 results signify that days since manure application is a significant factor, but that it has a moderate effect on P loss. Days since manure application had a moderate effect size compared to some of the other factors considered. However, the impact of manure application timing in this dataset is subtle (Figure 9), and the influence of frozen or non-frozen conditions may be more important when planning manure applications (Table 5). Overall, runoff events that occur closer to manure applications do have higher P loads and concentrations, and consideration of frozen or non-frozen conditions when manure is applied is important for understanding these losses.

The type of tillage was significant for TP, DP, TP FWMC, and DP FWMC. NT had the highest P losses, specifically DP and DP FWMC in frozen conditions, aligning with previous studies that show that NT can increase DP (Daryanto et al., 2017; Zopp et al., 2019; Singh et al, 2020). This is attributed to the lack of surface roughness and depressional storage as well as an accumulation of P in the top layers of soil due to its low mobility (Hansen et al., 2000). The stratification of soil P can vary depending on the length of NT and frequency of nutrient applications. Many of the sites in this dataset have high levels of STP in the top 0-5cm, possibly leading to higher DP and DP FWMC. The sites with the highest amount of STP at the 0-5cm depth were NT or RT. RT sites also had elevated P loss in frozen conditions compared to CT in this dataset. Since the RT sites do not mix soil as deeply or as often compared to CT, P stratification may be occurring. The amount of DP lost during frozen conditions was similar in both NT and RT sites, but DP FWMC loss due to snowmelt specifically was lower in RT sites compared to NT. In the findings from Liu et al. (2014), fields that transitioned from conservation tillage (minimal tillage except to redistribute residue) to rotational tillage (tillage only every second year), decreased DP FWMC by 46%, which largely came from snowmelt runoff. Increasing the frequency of tillage may help break up P stratification, leading to reductions of DP in snowmelt runoff. However, some stratification may occur when compared to CT sites. Model results showed NT as a significant factor with a large effect on DP and DP FWMC. Elevated TP FWMC in NT conditions can also be seen in the model results, with a large portion as DP FWMC (Figure 8). This indicates that particulate phosphorus loss is lowest in NT. NT had the largest effect on TP FWMC and DP FWMC in all of the models (Figures 9-11), suggesting that NT is the largest contributor to high concentrations of TP and DP. Monitoring STP at the 0-5cm depth and occasionally tilling the soil may reduce P losses.

High amounts of STP at the 0-5cm and 0-15cm depth moderately influenced DP and DP FWMC. The limited mobility of P means that the top 0-5cm are rich in P, especially when manure is applied frequently to NT fields (Andraski et al., 2003). This creates risk of P runoff when excess nutrients exist on the soil surface. DP is especially at risk of running off due to elevated STP on the soil surface (Sharpley et al., 1993; Pote et al., 1996). Sampling STP at both the 0-5cm and 0-15cm depth can provide better predictions to P loss from agricultural fields (Osterholz et al., 2020). Model 2 and 3 results showed STP 0-5cm to be significant to DP and with large effects on DP and DP FWMC. Surprisingly, STP had a negative coefficient at the 0-5cm depth with all the models, implying that there were decreases in P loss when STP at the 0-5cm depth increased. This may be due to the other factors included in the model. Observed results in the dataset did not have this same negative correlation, as regression results all showed positive slopes for STP 0-5cm and TP, DP, TP FWMC, and DP FWMC. The STP 0-15cm had a positive coefficient, but a smaller effect on DP and DP FWMC compared to the 0-5cm depth. The 0-15cm depth was only significant to TP FWMC and DP FWMC in model 3, suggesting that this depth is not as important as the 0-5cm depth in understanding DP loss.

The presence of a crop, residue, or lack of cover influences runoff characteristics. The greatest amount of TP loss in this dataset occurred during the no cover stage, reflecting results from Plach et al. (2019) which points to the nongrowing season as the high risk period for P loss in cold climates. Model results show the crop stage with the least amount of TP and DP loss (Figures 9, 11). Having an active crop growing can reduce the rate of runoff and provide a buffer to the soil, as the canopy can slow the impact of raindrops hitting the surface, thus reducing soil detachment and P loss (Ma et al., 2014). Likewise, plants uptake P throughout the growing season, reducing P in the soil. No cover conditions do not provide this same buffer and can leave the soil vulnerable to runoff. Residue left on the soil surface can help reduce the impact of raindrops, thus soil detachment and transport of P. In comparison to no cover conditions, leaving residue on the soil can reduce runoff. The model results show residue as having a smaller effect on TP and TP FWMC loss than no cover, thus fewer losses when runoff occurs with residue on the surface (Figure 10, Tables 3-5). However, residue can also be a source of P, particularly DP, as the residue decomposes and runoff occurs (Liu et al., 2014; Messiga et al., 2010). Models 1 and 3 show an increase in DP and DP FWMC in both residue and frozen conditions. This could imply that during freeze-thaw cycles, there is elevated DP loss (Table 3,5). Freeze-thaw cycles can accelerate the decomposition process, increasing the amount of nutrients released from residue and transported during snowmelt or rainfall on frozen soils (Bechmann et al., 2005; Liu et al., 2019). When comparing P loss of NT and tilled sites in the observed data, they had similar amounts of loss based on the surface condition. The most distinct differences could be seen in DP FWMC where tilled fields with residue have a statistically similar amount of loss at the NT crop stage, meaning that the surface condition in NT that has the least amount of P loss was similar to the surface condition of tilled sites that had the most P runoff.

Other variables considered in the models, such as crop, led to varied effect sizes. The model result did not show any single crop as significant across all of the models. Alfalfa had the lowest P loss from the observed data out of the crops in this study. This could possibly be due to the year-round cover provided, and that prior to seeding, the sites are tilled

(Supplemental figure 3). Alfalfa had fewer losses than the other crops considered in the models, but was not always significant to P loss and did not always have a large effect in comparison to the other crops. Results from Young and Mutchler (1976) compared manure applications on NT alfalfa with fall tilled continuous corn and found that alfalfa had higher runoff and P loss. They suggest that manure application on rough plowing, rather than applying to no till, helps reduce runoff. The alfalfa fields in this study are tilled before seeding, possibly reducing the amount of P on the soil surface. However, it can be several years before the sites are tilled again, potentially nullifying the effects of tillage years down the line. Comparing the effect of crop type did not reveal any conclusive results on their effect on P loss, but rather points to the other management conditions that may lead to increased P runoff.

The Natural Resources Conservation Service (NRCS) hydrologic group helps explain the runoff potential from a site, capturing the soil type and infiltration rate of a soil. These are classified A-D, A having the lowest runoff potential, and D having the highest. When more than one group applies to a site, the first letter represents that larger component of that site (NRCS, 2009). Hydrologic groups A, B, and C/D are all significant to the model results, particularly TP and TP FWMC. These factors generally had a large effect on P loss in the models, indicating that the hydrologic group is important to understanding the risk of P loss at a particular site. This provides more information on the runoff risk of each site, and how that influences P runoff.

TP and DP loads were significant with several weather variables within the model 3 results (Table 5). Rainfall intensity is an important consideration with P transport in runoff

(Shigaki et al., 2006). Multiple intensity variables were tested in the models, but the 5 minute max intensity improved both the marginal and conditional R^2 value and had the largest effect on P runoff compared to other models considered. Water infiltrates soils at a certain rate, which varies depending on the soil, so when rainfall intensity increases past that rate, runoff occurs. Out of the weather characteristics considered (precipitation, storm duration, average intensity, 5 minute max intensity, and antecedent rainfall 2 day), 5 minute max intensity had the second largest effect on TP and the largest effect on TP FWMC. High intensity rainfall may displace soil, which is associated with increased particulate P (PP) loss (Fraser et al., 1999; Sporre-Moeny et al., 2004). The more intense period may have increased TP and TP FWMC loss due to a greater proportion of PP in the sample. Likewise, antecedent rainfall was significant to P loads. More saturated soils may be at risk for more runoff, as the water holding capacity of the soil peaks during the storm. Danz et al., (2013) describe antecedent rainfall as one of the most important runoff characteristics to TP loads, as it provides information on the amount of water in the watershed leading to the runoff event.

All of the LMM results had both marginal and conditional R^2 ranging from 0.17-0.44, showing that there is variability unaccounted for within the models. Each successive model increased the R^2, but reduced the number of observations included. Model 2 was important to show the significance of manure application timing. Since some sites did not apply manure, this reduced the number of sites included. Model 3 had the highest R^2, likely due to the inclusion of more specific weather variables in comparison to the other models (Table 4). However, this further reduced the observation size (n=973), and snowmelt events were not included, as snow water equivalent amounts were not collected by the edge-of-field monitors.

Likewise, a binary factor for manure application (0 for manure applied, 1 for no manure applied) was used in model 3. Including both the weather variables and the number of days since manure application reduced the observation size considerably, which is why we did not include it in these findings. For stronger models, the inclusion of continuous weather data and manure timing would be important. A larger dataset that included snow water equivalent amounts and days since manure application in the same model would help improve LMMs.

CONCLUSIONS AND FUTURE RESEARCH:

This study provides information on how the timing of manure applications, surface condition, tillage, STP, and weather conditions effect edge-of-field P runoff in Wisconsin and Minnesota. Long term edge-of-field monitoring provides the data necessary to identify which factors may be responsible for increased P loss. Then, utilizing LMM methods, these factors can be compared to understand their relative effect on P runoff.

Several key findings emerged from both the exploratory analysis and modeling results. First, this study shows that the timing of manure applications only has a marginal effect on P loads and concentrations. Both model and observed results show that P loss is the highest close to a manure application and decreases over time. Site-by-site analysis of DF sites may provide further insight on which factors lead to high loads and concentrations in P runoff long after manure applications. Second, this research highlights the impact of NT on P loss. Increased DP loads and concentrations are seen in NT sites, especially in frozen conditions. Model results point to the large effect that NT conditions have on DP losses, particularly in the 0-5cm depth. Third, the sites in this study had high amounts of STP at both the 0-5cm and 0-15cm depths, and model results showed DP and DP FWMC loss were influenced by STP at the 0-5cm depth. STP should be monitored at both the 0-15cm and 0-5cm depths to understand the P runoff risk. Fourth, this shows the slight differences between residue and no cover surface conditions. During the growing season, a crop that has reached a canopy stage can reduce P losses. Outside of that period, residue can also show reductions in TP and TP FWMC. However, during frozen periods, residue can act as a source of DP due to decomposition. Further study of these processes could provide more information on the effectiveness of residue in reducing P loss during the winter and early spring periods.

LMM methods can be applied to other unstructured agricultural datasets to understand which practices may be having a large effect on P loss. In particular, the models in this study had a wide range of R^2, showing high variability based on the factors included. For further improvement, incorporating both the number of days since manure application and weather variables, including snowmelt data, may increase the R^2 of the models. This would provide a deeper understanding of how these significant factors influence P runoff in cold climates.

This study highlights the importance of long-term edge-of-field monitoring. Continued investment in these types of studies is important to further our understanding of the drivers of nutrient loss in agriculture sites. Future work including more sites could provide a larger distribution of STP values, tillage practices, and soil characteristics, which could improve our understanding of P losses.

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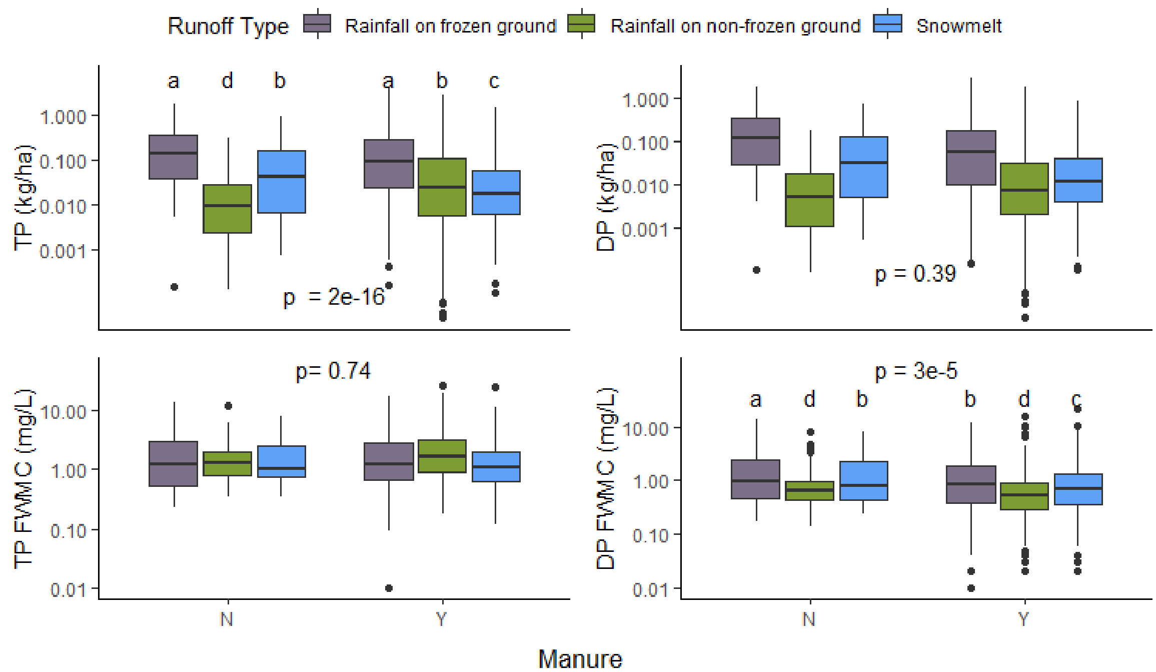
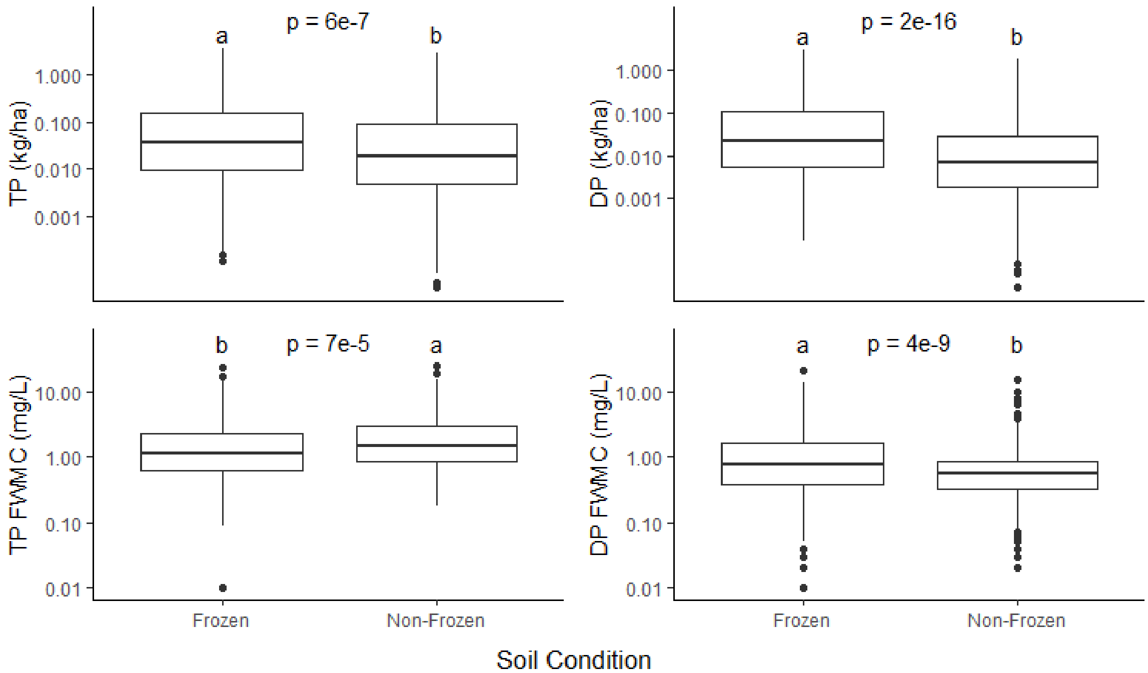
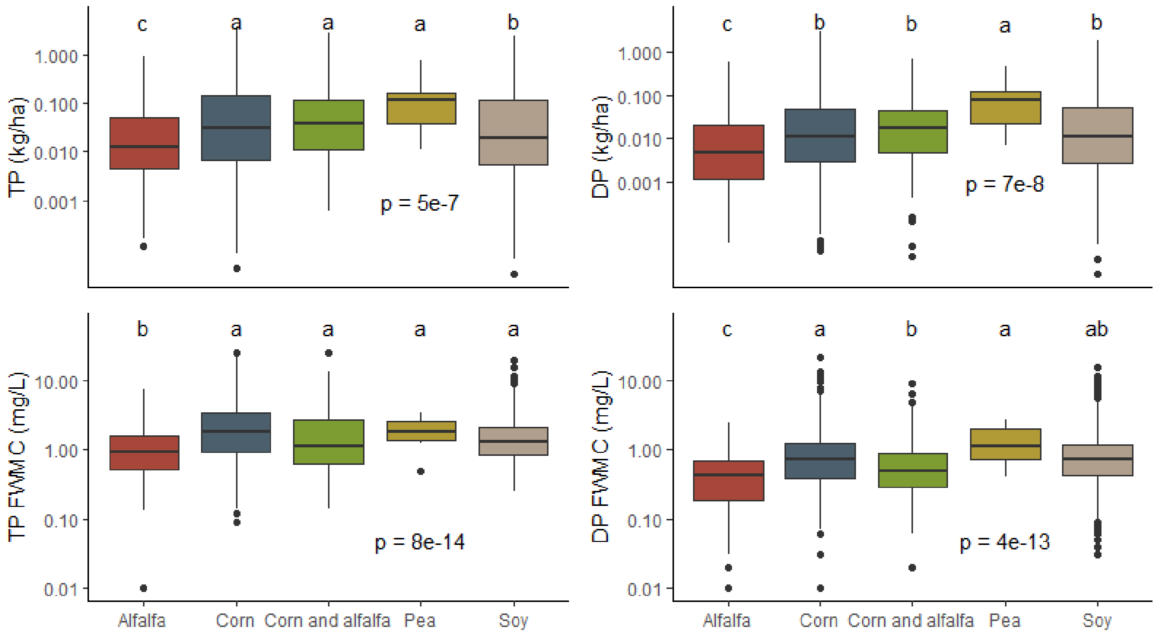
Supplemental Information:



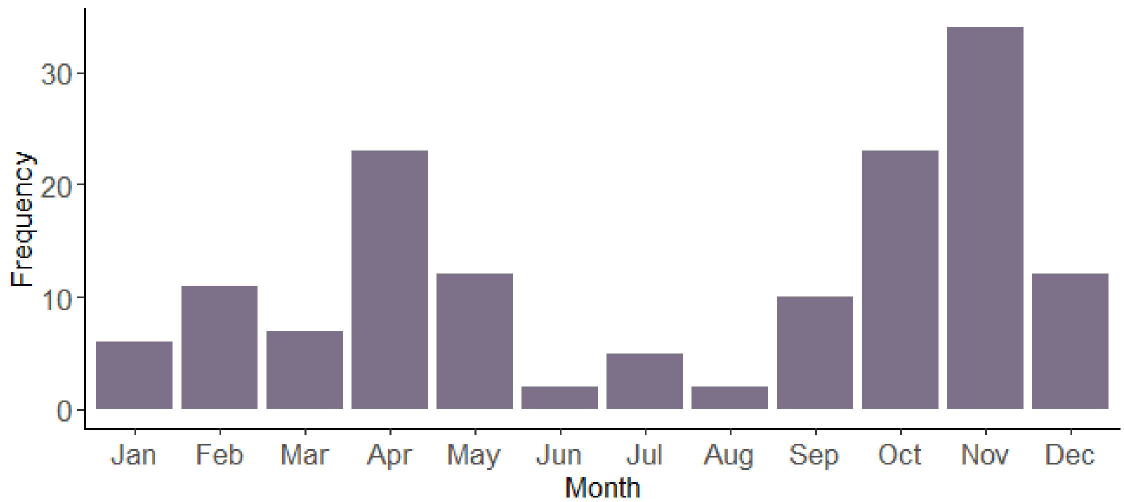
Supplemental Figure 1. Boxplots of fields with or without manure application (n=1339), and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.



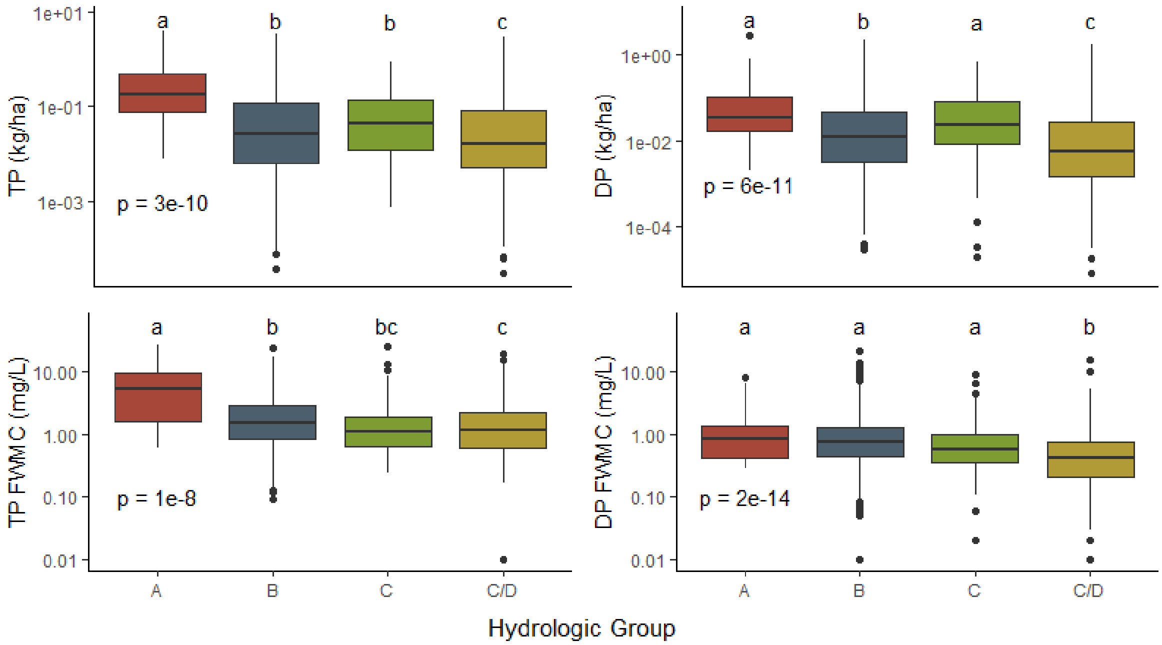
Supplemental figure 2. Boxplots of soil condition (n=1339), and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.



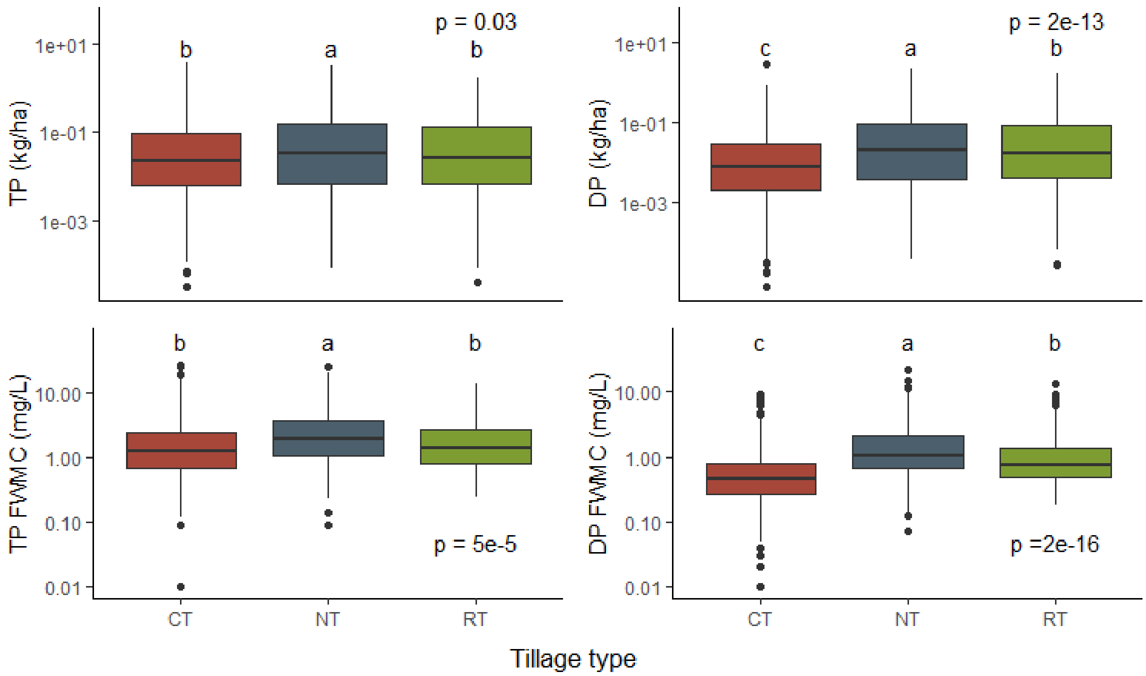
Supplemental Figure 3. Boxplots of crop type, and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.



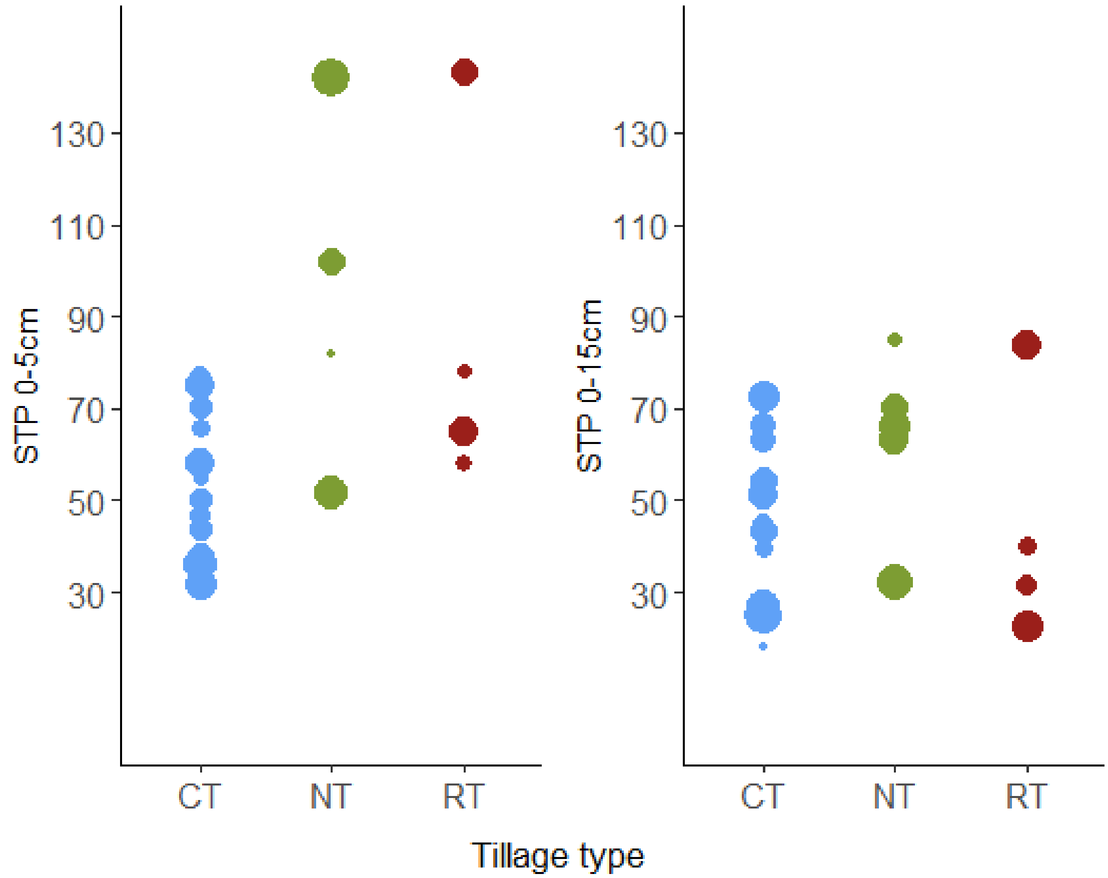
Supplemental Figure 4. Distribution of manure applications by month (n = 147).



Supplemental Figure 5. Boxplots of hydrologic soil group, and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.



Supplemental Figure 6. Boxplots of conventional tillage (CT), no till (NT), and reduced tillage (RT), and total phosphorus load (TP), dissolved phosphorus load (DP), total phosphorus flow-weighted mean concentration (TP FWMC), and dissolved phosphorus flow-weighted mean concentration (DP FWMC). The lower and upper ends of the boxplots represent the 25th and 75th percentile, the bolded line in the middle of each boxplot represents the median. Outliers are the points outside the lines. Treatments with different letters represent differences based on the least significant difference test using log transformed TP, DP, TP FWMC, and DP FWMC. Figure was plotted using observed data on a log scale.



Supplemental Figure 7. Counts of conventional tillage (CT), no till (NT), and reduced tillage (RT), and soil test phosphorus (STP) at the 0-5cm and 0-15cm depths.

Supplemental Table 1. Summary statistics of independent weather variables and STP at the 0-5cm and 0-15cm depths

	Precipitation (mm)	Storm Duration (hrs)	Average Intensity	5 Min Max Int.	10 Min Max Int.	15 Min Max Int.	30 Min Max Int.	60 Min Max Int.	Antecedent Rainfall 1 Day (in)	Antecedent Rainfall 2 Day (in)	Antecedent Rainfall 3 Day (in)	STP 0-15cm (ppm)	STP 0-5cm (ppm)
n	987	987	987	987	987	987	986	987	986	986	984	1339	1319
Minimum	0.46	0.05	0.01	0.11	0.05	0.04	0.02	0.01	0	0	0	18	32
1st Quartile	11.89	2.32	0.08	0.48	0.38	0.34	0.28	0.21	0	0	0.01	25.7	46.5
Mean	15.9	6.21	0.31	2.07	1.61	1.34	0.93	0.59	0.24	0.45	0.64	46.46	70.44
Median	22.4	4.47	0.19	1.68	1.32	1.04	0.72	0.46	0.01	0.11	0.24	43.2	65
3rd Quartile	36.07	8.2	0.38	3.28	2.4	2.04	1.38	0.87	0.29	0.6605	0.92	66.25	77.25
Maximum	246	80.77	3.56	9.72	6.68	6.24	5.5	4.7	2.56	5.82	5.83	85	143
Std. Dev.	22.39	6.22	0.36	1.73	1.39	1.17	0.82	0.52	0.42	0.7	0.88	20.4	33.15
CV	1.41	1	1.16	0.84	0.86	0.87	0.88	0.88	1.75	1.56	1.38	0.44	0.47
Skewness	2.4	3.85	2.98	0.89	1	1.13	1.55	2.18	2.3	2.5	2	0.29	1.21
Kurtosis	12.12	29.49	13.54	0.33	0.55	1.21	3.73	9.36	5.52	9.36	4.84	-1.19	0.63

Supplemental Table 2. Regression results for Runoff, Soil, TP, DP, Soil FWMC, TP FWMC, and DP FWMC. Slopes were reported when p $\leq$ 0.05

	Runoff (mm)			Soil (kg/ha)			TP (kg/ha)			DP (kg/ha)			Soil FWMC (mg/L)			TP FWMC (mg/L)			DP FWMC (mg/L)		
	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2
Precipitation (in)	1.00E-09	+	0.04	2.00E-16	+	0.1	3.00E-10	+	0.04	2.00E-06	-	0.02	4.00E-13	+	0.052	0.86	NS	3.00E-05	0.44	NS	6.00E-04
Storm Duration	6.00E-11	+	0.04	0.57	NS	3.00E-04	5.00E-05	+	0.02	5.00E-08	+	0.02	2.00E-07	-	0.03	0.002	-	0.01	0.99	NS	6.00E-09
Average Intensity	3.00E-03	-	0.009	3.00E-07	+	0.03	0.37	NS	8.00E-04	0.002	+	0.01	2.00E-16	+	0.084	3.00E-04	+	0.01	0.65	NS	2.00E-04
5 Min Max Int.	0.58	NS	3.00E-04	2.00E-16	+	0.12	0.002	+	0.01	0.53	NS	4.00E-04	2.00E-16	+	0.19	1.00E-09	+	0.04	0.61	NS	3.00E-04
10 Min Max Int.	0.4	NS	0.0007	2.00E-16	+	0.12	0.002	+	0.01	0.59	NS	3.00E-04	2.00E-16	+	0.17	6.00E-08	+	0.03	0.84	NS	4.00E-05
15 Min Max Int.	0.27	NS	0.001	2.00E-16	+	0.12	0.002	+	0.01	0.69	NS	2.00E-04	2.00E-16	+	0.16	7.00E-07	+	0.03	0.99	NS	2.00E-05
30 Min Max Int.	0.04	+	4.00E-03	2.00E-16	+	0.12	2.00E-04	+	0.01	0.62	NS	3.00E-04	2.00E-16	+	0.15	1.00E-05	+	0.02	0.89	NS	2.00E-05
60 Min Max Int.	0.006	+	0.008	2.00E-16	+	0.12	2.00E-05	+	0.02	0.16	NS	0.002	2.00E-16	+	0.13	3.00E-05	+	0.02	0.57	NS	3.00E-04
Antecedent Rainfall 1 Day	0.81	NS	6.00E-05	2.00E-04	+	0.02	0.14	NS	0.002	0.39	NS	0.0008	1.00E-05	+	0.02	0.1	NS	0.003	0.32	NS	0.001
Antecedent Rainfall 2 Day	0.48	NS	5.00E-04	4.00E-05	+	0.02	0.44	NS	6.00E-04	0.92	NS	1.00E-05	1.00E-05	+	0.02	0.76	NS	9.00E-05	0.62	NS	3.00E-04
Antecedent Rainfall 3 Day	0.84	NS	4.00E-05	1.00E-05	+	0.02	0.97	NS	2.00E-06	0.23	NS	0.002	2.00E-07	+	0.03	0.91	NS	1.00E-06	0.13	NS	0.002
STP 1-2 ppm	0.005	-	0.006	0.05	-	0.003	0.01	+	0.005	1.00E-07	+	0.02	0.88	NS	2.00E-05	4.00E-08	+	0.02	3.00E-14	+	0.04
STP 6 ppm	3.00E-05	-	0.01	0.93	NS	7.00E-06	0.23	NS	1.00E-03	1.00E-02	+	0.005	4.00E-05	+	0.01	1.00E-05	+	0.01	6.00E-08	+	0.02

Supplemental Table 3. Regression results for Runoff, Soil, TP, DP, Soil FWMC, TP FWMC, and DP FWMC. Slopes were reported when $p \leq 0.05$

	Runoff (mm)			Soil (kg/ha)			TP (kg/ha)			DP (kg/ha)			Soil FWMC (mg/L)			TP FWMC (mg/L)			DP FWMC (mg/L)		
	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2	P-value	Slope	R2
Days since:																					
Harvest	0.01	+	0.006	0.09	NS	0.005	0.27	NS	0.001	0.06	NS	0.003	4.00E-06	-	0.02	0.41	NS	6.00E-04	0.28	NS	0.001
Tillage	0.02	+	6.00E-03	3.00E-08	-	0.03	0.2	NS	0.002	0.03	NS	0.005	2.00E-16	-	0.08	3.00E-05	-	0.02	0.21	NS	0.002
Nutrient Application	0.0007	-	0.009	6.00E-06	-	0.017	8.00E-12	-	0.04	3.00E-09	-	0.03	0.01	-	0.005	4.00E-07	-	0.02	2.00E-04	-	0.012
Manure Application	1.00E-06	-	0.02	0.002	-	0.01	2.00E-16	-	0.08	2.00E-16	-	0.08	0.84	NS	4.00E-05	4.00E-14	-	0.05	2.00E-16	-	0.07
N Fertilizer	0.15	NS	0.002	2.00E-10	-	0.04	2.00E-6	-	0.02	5.00E-04	-	0.01	2.00E-10	-	0.04	5.00E-06	-	0.02	0.005	-	0.007
P Fertilizer	0.65	NS	3.00E-04	5.00E-13	-	0.07	3.00E-06	-	0.03	0.02	-	0.73	2.00E-16	-	0.11	2.00E-16	-	0.1	6.00E-07	-	0.03
Any N application	0.01	-	0.006	9.00E-08	-	0.02	8.00E-12	-	0.04	4.00E-10	-	0.03	2.00E-05	-	0.02	8.00E-11	-	0.03	3.00E-09	-	0.03
Any P application	0.02	-	0.004	7.00E-06	-	0.02	2.00E-10	-	0.03	2.00E-08	-	0.03	5.00E-04	-	0.01	9.00E-09	-	0.03	9.00E-06	-	0.02
Runoff events since:																					
Any N Application	0.0001	-	0.01	0.003	+	0.01	2.00E-16	+	0.06	2.00E-16	+	0.06	0.21	NS	0.001	2.00E-16	+	0.06	2.00E-16	+	0.07
Any P Application	0.01	-	0.006	0.002	-	0.008	4.00E-13	-	0.04	6.00E-14	-	0.05	0.17	NS	0.002	2.00E-14	-	0.05	9.00E-16	-	0.05
Manure Application	0.001	-	0.01	0.1	NS	0.003	6.00E-14	-	0.05	2.00E-16	-	0.06	0.26	NS	0.001	1.00E-13	-	0.05	2.00E-16	-	0.08
Any Nutrient Application	2.00E-06	-	0.02	0.0008	-	0.01	2.00E-16	-	0.06	2.00E-16	-	0.06	0.96	NS	2.00E-06	3.00E-13	-	0.04	2.00E-16	-	0.05
Tillage	0.002	+	0.01	0.002	-	0.01	0.56	NS	4.00E-04	0.16	NS	0.002	2.00E-10	-	0.04	2.00E-06	-	0.03	0.11	NS	0.003

Supplemental Table 4. Manure information by site

Site	**Source**	**Placement**
AR1	Beef	Surface
AR2	Beef	Surface
BE1-F	Swine	Injected
DO1-F	Swine	Injected
GO1-F	Swine	Injected
H3	Dairy or Poultry	Surface applied or Incorporated within 72 hrs
JF4	Dairy	Surface applied
JF5	Dairy	Injected or Surface applied
KP3	Dairy	Surface applied
P1	Dairy	Injected or Surface applied
P2	Dairy	Injected or Surface applied
P3	Dairy	Injected, Surface applied, or Incorporated within 72 hrs
R1	Beef or Dairy	Surface applied
R2	Beef or Dairy	Surface applied
R3	Beef or Dairy	Surface applied
RO1-F	Beef	Surface applied
ST1-F	Dairy	Injected
WF1	Poultry	Surface
WR1-F	Dairy	Injected