Influence of phosphorus management on potential for soluble phosphorus loss through leaching

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ABSTRACT

The over application of phosphorus (P) fertilizers in agricultural systems may pose a threat to water quality due to the loss of dissolved P to fresh water bodies leading to eutrophication. The objectives of this study were to evaluate the potential for water soluble P loss from top soil (0-6 inches) across a range of initial soil test phosphorus (STP) levels, soil types, and leaching volumes; and to determine if P leaching loss could be predicted with existing soil P tests. Intact soil columns were collected from six field sites throughout Minnesota representing soils at four STP levels. Columns were leached with deionized water at ten times field capacity for each corresponding soil type. Leaching was repeated for a second set of columns from Low testing P soils at three sites with various volumes of deionized water: 200 mL, 400mL, and 600 mL. Leachate was collected and analyzed for water extractable P (WEP) colorimetrically to approximate P loads in both experiments. Soil type and STP level both influenced the amount of P leached. Phosphorus concentration did not vary in leachate among soil types, thus the amount of P lost was dependent of the total water leached through the soil (P load). When the leaching volume was increased, the total amount of P leached increased proportionally for all three soils. Existing soil P tests correlated with P leaching, however, the results from this study indicate P leaching was best predicted according to volume of the leaching event.

INTRODUCTION

Phosphorus (P) is a critical nutrient for maximizing yield in corn-soybean systems across the state of Minnesota. Excess P from fertilizers in agricultural systems can become an environmental pollutant and cause water quality issues such as eutrophication of freshwater systems (United States Environmental Protection Agency, 2000; Boesch et al., 2001; Maguire & Sims, 2002). In 2004, agriculture accounted for 29 percent of eutrophication throughout the state of Minnesota (MPCA and Barr Engineering Company, 2004). The source of this P pollution has been largely attributed to surface runoff from agricultural fields (Sharpley et al., 2001; Deasy et al., 2010).

As the principle P loss pathway, research concerning phosphorus loss has largely focused on surface runoff. Other loss pathways, such as P leaching, have been considered insignificant in comparison to runoff and erosion (Sims et al., 1998). In recent years, studies have pointed to leaching as a greater threat, especially with soils with high initial soil test P (STP) levels (Heckrath et al., 1995; July et al., 1999; Hooda et al., 2000; McDowell & Sharpley, 2001). There is evidence to suggest increasing P levels above recommended agronomic levels leads to higher P losses (July et al., 1999; Maguire & Sims, 2002). In Minnesota, repeated P fertilization to agricultural fields can lead to P enriched soils, potentially leading to higher susceptibility for P loss through leaching and runoff (Sims et al., 1998; July et al., 1999).

Connecting P loss via leaching to soil P content poses many challenges to researchers. Imitation soil columns containing dry, sieved, and packed soil often lack the transport mechanisms and field hydrology of a typical soil. Furthermore, the form of P applied to the soil, inorganic versus organic, may influence P leaching or binding potential, requiring research sites have a specific P application history (Kang et al., 2011). Projecting P leaching losses from a sample to the landscape can also be misleading, as water loss and movement can greatly vary due to physical and chemical properties. While most studies simulate an average rainfall event to quantify leaching, the range of precipitation widely varies, even across states. Average precipitation in Minnesota ranges from 18 inches in the northwest to 32 inches in the southeast (Minnesota Pollution Control Agency, 2015). Moreover, in a changing climate with the frequency and intensity of precipitation events increasing, researchers have yet to identify how this will influence P leaching (Minnesota Pollution Control Agency, 2017). The influence of water volume on P loss in agricultural soil has yet to be identified. To most successfully estimate P loss for a region, experimental units should include several soil types with a range of initial STP levels under a consistent P application method. Leaching at several water volume levels may also offer insight to the influence of precipitation frequency and intensity on soluble P loss.

The objectives of this study are to 1) Determine how building soil test P levels across contrasting soils influences the leaching loss of soluble P in the topsoil; 2) Determine if P leaching potential could be predicted with existing soil P tests, soil properties, or amount of water moving through the soil profile; 3) Evaluate the influence of water volume in a leaching event on soluble P loss.

MATERIALS AND METHODS

Site Description

The samples for this experiment were collected from six locations across the state of Minnesota. The sites for this experiment were selected intentionally as they were part of a long-term phosphorus study under consistent P management since 2010 (Sims et al., 2014). At each location, soil test phosphorus (STP) levels ranged from Low to Very High categorized by the Olsen P routine soil test and classified by current Minnesota suggestions for corn and soybean production (Table 1). Soils were maintained at these levels with annual P_2O_5 applications. All soil test levels were significantly different from one another across locations, except for the Low and Medium testing soils (Table 2). Soil types selected for the experiment ranged from sandy loam to clay loam with varying physical and chemical properties (Table 3).

Table 1. Minnesota Soil Test P level classifications according to current University of Minnesota guidelines (Kaiser et al., 2011).

Extractant	V. Low	Low	Medium	High	V. High
	---------------------------- ppm P in soil----------------------------				
Bray-P1	0-5	6-10	11-15	16-20	21+
Olsen P	0-3	4-7	8-11	12-15	16+

Table 2. Significant differences between each of the four soil test phosphorus (STP) levels (Low, Medium, High, Very High) according to Olsen P soil test values across six sites in Minnesota.

	Low	Medium	High
Medium	ns†		
High	***	***	
V. High	***	***	***

† Pairwise comparisons using t-tests to identify significant differences between STP levels based on Olsen P soil test values. Signif. codes: $P \leq 0.001$'***'; $P \leq 0.01$'**'; $P \leq 0.05$ '*'; ns: not significant at $\alpha = 0.05$

Table 3. Soil series, taxonomy, physical, and chemical properties for six study locations in Minnesota determined from composite soil samples.

	Soil						
Site	Series	Taxonomy†	Texture‡	**Bulk density**	**Field capacity**	**pH**	**CCE**§
				g cm^{-3}	mL		%
Becker*	Hubbard	En Hapludoll	S Loam	1.40	21.3	6.5	0.3
Crookston	Gunclub	Ae Calciaquoll	Cl Loam	1.20	46.2	7.9	4.7
Lamberton	Normania	Ca Hapludoll	Cl Loam	1.17	46.5	5.4	0.1
Lawlers*	Mt. Carroll	Mo Haludalf	Si Loam	1.17	42.4	7.2	0.4
Morris	Dolan	Aq Calciudoll	Si Loam	1.24	40.2	7.7	2.4
Waseca*	Webster	Aq Hapludoll	C Loam	1.18	50.3	5.9	0.2

* Sampled in following year for follow-up volume study;
† Soil taxonomy abbreviations: Aquic (Aq), Mollic (Mo), Calcic (Ca), Aeric (Ae), Entic (En)
‡ Soil texture abbreviations: Sandy (S), Silt (Si), Loam (L), Clay (C), determined by hydrometer method;
§ CCE: Calcium Carbonate Equivalent

Sampling

Sixteen plots were selected to represent soils maintained at Low, Medium, High, and Very High STP levels at each location. Soil columns (1.5-inch diameter) were taken from each of the sixteen plots to a depth of six inches in PVC columns using a tractor operated hydraulic soil probe. The bottom edge of the PVC columns was beveled to help alleviate sidewall soil compaction in the columns. Columns were capped and stored in coolers and kept in cold storage at 40°F at the lab site. Eight soil cores, six inches deep, were collected and composited from near the PVC collection sites for a representative soil sample for chemical analysis. The composite soil samples were analyzed in the lab for P content and chemical properties to correspond with leaching columns.

An additional set of columns and corresponding soil samples were drawn from Low testing P plots at 3 sites for a leaching volume study. Three columns were drawn at each plot for each of the three volumes to be tested. Replication was at the plot level, as plots selected were all at the Low STP level. Sites varying in soil texture and other properties were selected for testing in the volume study (Table 3).

Leaching Procedure

Columns were removed from cold storage and allowed to reach room temperature before leaching. Sixteen columns were leached per run. Water drained freely through the columns initially. Vacuum was applied as needed at a pressure of 10 bar (pressure at field capacity) to ensure all gravitational water was drained from the column and to keep the column leaching rate consistent throughout the experiment. A cap with a nipple fitting was placed on the bottom of each column and attached to a filter flask by PVC tubing. Glass wool was packed in the bottom of the column to prevent soil loss from the tube. Leachate was collected in a 500mL filtering flask and weighed to determine the mass of water leached through the tube.

Field capacity was calculated for each soil site to standardize the amount of water to draw through soil columns at each site (Table 3) relative to the water holding capacity. Each column was leached at 10 times field capacity to ensure a leaching event would occur across all various soil types and to standardize the amount of water leached relative to the water holding at field capacity. A portion of the leachate was filtered through Whatman no. 42 filter paper and analyzed colorimetrically with a photospectrometer for water soluble P using methods from Murphy and Riley (1962).

Phosphorus loss was quantified in three ways: P concentration (ppm), total P leached per column (P load), and P load normalized using the dry weight of soil in each column (P loss per unit soil). Phosphorus concentration was the ppm P reading from a subsample of the leachate from every column. Leachate mass was used to calculate P load based on the concentration of P (ppm P) in the leached solution and total volume leached per column (mg P column^{-1}). To further standardize leaching of P, dry soil weight of each column was measured to allow for statistical analysis for P leaching loss as P leached per unit soil (µg P g soil^{-1}). Soil was emptied from each column and weighed. A subsample of soil from each column was dried and weighed to calculate moisture and total dry soil column weight.

In the second experiment with columns from Low testing plots, soils were leached in the same leaching apparatus using the same procedure outlined above. Columns received one of the three volume treatments: 200 mL, 400 mL, or 600 mL of deionized water. All analyses followed similar procedures as outlined for the STP comparison experiment above.

Soil Sample Analysis

Composite soil samples were analyzed for pH [1:1 soil/water (Watson and Brown,1998)], Bray-P1 and the Olsen P extractable P (Frank et al., 1998). Water Extractable Phosphorus (WEP) and Bio-Available P (Bio P) were measured onsite using methods from Pote et al. (1999) and Chardon (2000) respectively. All composite soil samples were also tested for carbonate content by the modified pressure calcimeter method (Sherrod et al., 2002).

Statistical Analysis

Collection of soil tubes from replicated plots allowed for analysis of the data to determine differences between fixed effects of soil type, initial STP level, water volume as well as random block effects. Statistical analysis for this experiment was completed in R using linear regression, ANOVA, ANCOVA, pairwise t-test, and Tukey's HSD (honest significant difference) and Fisher's LSD (least significant difference) mean separation tests (R Development Core Team, 2007). Correlation between soil P extraction methods and P leachate measurements was also conducted in R using Pearson's Correlation.

RESULTS AND DISCUSSION

Influence of Soil Type (site) on P Leaching Loss

A pairwise t-test showed significant differences between sites when measuring loss as P load (mg P column^{-1}) and P leached per unit soil (µg P g soil^{-1}), but sites were not significantly different when loss was measured as P concentration (ppm P). The three quantifications of P loss also resulted in different ordering of sites from greatest to least P leaching loss. However, there were no significant differences between sites when rank order changed. Further examination with an HSD test specified differences between sites for each P quantification method (Table 4).

Leaching losses, as measured by P load, were greatest at Waseca followed by Lamberton, Morris, Crookston, Lawlers, and lastly Becker. Becker was leached with approximately half as much water as the other sites due to its low water holding capacity (Table 3), and in turn leached the lowest amount of P. The follow up volume study indicated the amount of leachate may have influenced this lower P leaching value, which will be discussed at length below.

Table 4. Average P leached per unit soil, P concentration, and P Load values for soil columns from six Minnesota sites.

Site	P leached per unit soil	P Concentration	P Load
	μg P g soil^{-1} (ppm)	mg P L water^{-1} (ppm)	mg P column^{-1}
Becker	0.16 c†	0.31 a	0.05 b
Morris	0.60 b	0.44 a	0.16 a
Crookston	0.65 ab	0.39 a	0.16 a
Lawlers	0.69 ab	0.37 a	0.14 a
Waseca	0.84 ab	0.40 a	0.19 a
Lamberton	0.90 a	0.31 a	0.18 a

†Letters indicate significant difference of P leaching between sites according to Tukey's HSD test. Values within columns with the same letter are not significantly different at $P \leq 0.05$.

Accurately Representing P Leaching Loss

The discrepancy between the P measurements indicated method of P loss quantification should be considered to avoid misrepresentation of leaching loss. Phosphorus load is not standardized for the weight of soil in each individual column, perhaps simplifying leaching losses. Predicting P leaching loss per unit of soil may also lead to some discrepancies due to differences in bulk density. While the overall average of the P leachate loss per unit soil increased across all sites (Figure 1), this comparison may be misleading for sandy soils, such as soils at the Becker site. Balancing the leachate to the mass of the soil does not consider the bulk density of sand relative to other soil textures therefore underestimating loss from sandier soils. This may have been the case for Becker soils, as the values balanced for soil mass (μg P g soil^{-1}) are lower than P concentration values (ppm P), unlike the averages for all sites (Figure 2). Phosphorus Load (P load) may be the most consistent predictor, as it is possible to predict phosphorus loss without bulk density so long as water movement can accurately be quantified for soils.

Phosphorus concentration of leachate over simplifies leaching loss and is not recommended as a method for quantifying P leaching loss. Phosphorus concentration was not significantly different across soil types, indicating P leaching losses were not different between sites. This measurement inaccurately represented P leaching loss without standardization for total leachate volume.

Influence of Initial STP Level

When averaged over all sites, all three measurements of P leaching followed the same trend: P loss increased with increased initial STP level (Figure 1). Initial STP level significantly influenced amount of P loss via leaching for all quantifications of P for sites pooled together. While P load, P concentration, and P leached per unit soil increased as the initial STP level increased, only the Very High STP level was significantly different from the other STP levels. Leachate from Low, Medium and High STP levels were not significantly different from one another in the analysis including all sites (Figure 3).

Sites examined individually indicated the Very High STP level leached greater amounts of P in comparison to the Low STP level at three of the six sites: Crookston, Lamberton, and Morris (Table 5). At Waseca, Becker, and Lawlers, P leaching losses were not significantly influenced STP level. Mean averages at these sites did however show an upward trend in P loss with increasing initial STP level. A LSD test indicated P leaching loss was significantly different between at least two STP levels all sites (data not shown).

Table 5. Average P leached (P load) across four soil test phosphorus levels for soil columns from six sites in Minnesota.

Site	Low	Medium	High	V. High
	------------------------------- mg P column^{-1} -------------------------------			
Becker	0.05 a†	0.06 a	0.04 a	0.07 a
Crookston	0.13 b	0.11 b	0.15 ab	0.25 a
Lamberton	0.11 b	0.16 ab	0.19 ab	0.26 a
Lawlers	0.09 a	0.11 a	0.14 a	0.22 a
Morris	0.09 b	0.12 b	0.16 ab	0.27 a
Waseca	0.18 a	0.14 a	0.19 a	0.24 a

†Letters indicate significant differences between STP levels for each site according to Tukey's HSD test. Numbers within rows followed by the same letter are not significantly different at $P \leq 0.05$.

Relationship with Soil P Extraction Methods

Correlations were calculated between soil P extraction methods and leachate measurements. Averaged across all sites, soil P extraction methods showed significant correlations with P leaching loss values (Table 6). The P leaching value, P load, had the strongest correlation with Bio P (r =0.69) followed by the Olsen P extraction method (r = 0.63). The Bray-P1 extraction method had the lowest correlation with P leachate values, and also with Water P values, indicating the Bray-P1 may not be the most effective test to estimate WEP losses or WEP in soil.

Table 6. Relationship among soil P extraction methods (Bray-P1, Olsen P, Water Extractable P, and Bio-Available P) and P leachate measurements (P leached per unit soil, P load, and P concentration). Values obtained from soil samples and leaching cores from six sites in Minnesota.

	Bray P1	Olsen P	Water P	Bio P	Leachate P	P Load
Olsen P	0.87†					
Water P	0.69	0.83				

Bio P	0.82	0.96	0.85			
Leachate P	0.53	0.65	0.62	0.67		
P load	0.46	0.63	0.60	0.69	0.92	
µg P g soil^{-1}	0.45	0.60	0.53	0.68	0.86	0.97

†Values displayed as correlation (r) values, where n=96. Correlation is significant when r ≥ 0.2.

The greater correlation with Olsen P could be due to the alkalinity of the soil test. In high carbonate soils, such as Morris and Crookston, the Olsen P is more accurate than the Bray-P1 extractant. Correlations were averaged over all sites, and this may explain the better performance of the Olsen P extraction method. Further examination of correlation data and calibration of these tests could potentially be used to estimate P leaching.

Influence of Volume on Leaching Loss

The consistently lower leaching values from Becker soil columns in the initial experiment led to a follow up study to identify the influence of leaching volume on P leaching losses. This preliminary study indicated significant differences in P leaching losses due to both soil type and volume of deionized water applied to columns. The three measurements of P suggested once again that the total amount of water leached through the column and the mass of the soil in the column significantly influenced P leaching loss predictions. Both P load and P leached per unit soil were significantly different between soil types and volumes. P concentration was not significantly different between leaching volumes, but slightly significant for soil type. This was further indication that P concentration of a subsample cannot represent leaching loss without standardizing with volume leached, or further, by soil mass. The mean across all volumes for P concentration was 0.10 ppm. Using Tukey’s HSD test, P concentration averages were found to be greatest for Becker (0.11 ppm), followed by Lawlers (0.09 ppm), and then (Waseca 0.07 ppm). This supported the theory that sandy soils, silt soils, and clay soils would leach the greatest to least amount of P respectively. However, P concentration estimate did not consider total volume of the sample, and cannot be used to make accurate loss predictions.

Table 7. Average P leached per unit soil and average P load (mg P column^{-1}) for each leaching volume for soil columns from three Minnesota soils.

Volume	200	400	600	200	400	600
Site	P leached per unit soil			P load		
	------------ µg P g soil^{-1} ------------			------------ mg P column^{-1} ------------		
Becker	0.05 b†	0.14 a	0.18 a	0.02 b	0.04 a	0.05 a
Lawlers	0.09 c	0.17 b	0.25 a	0.02 c	0.03 b	0.04 a
Waseca	0.03 b	0.04 b	0.18 a	0.01 b	0.01 b	0.04 a

†Letters indicate significant differences between leaching volumes for each site according to Tukey’s HSD test. Numbers within rows followed by the same letter are not significantly different from one another at *P* ≤ 0.05.

Analysis across the three soil types revealed greater P loss (P load and P leached per unit soil) as leaching volume increased from 200 ml to 400 ml and then 600 ml (Figure 5). Again, P concentration was not statistically different between leaching volumes. Balancing P load for soil mass led to different rankings of P leaching loss across soil types. Like the P concentration, P load indicated the sandy soil (Becker) leached the greatest amount, followed by the silt loam (Lawlers) and then clay loam (Waseca). However, when soil mass was included in the P leaching loss equation, as μg P g soil^{-1}, the silt loam (Lawlers) leached the greatest amount of P per unit soil, followed by the sand and then clay loam (Figure 4). This further highlighted the need to account for differences in bulk density for varying soil types when approximating P losses so to not over or underestimate P loss per unit soil.

All individual soil types showed increased leaching volume significantly increased P leaching losses (Table 7). An ANOVA and ANCOVA analysis indicated the regression slopes for each site were not significantly different. While sites had varying initial leaching losses, the leaching rate increased at a statistically similar rate across all soil types (Figure 5). With greater investigation, this could be a potential indicator for leaching loss potential for soils in Minnesota. As this was a preliminary study, further data is needed including more leaching volumes across additional soil types to determine if volume of a leaching event is as indicative of leaching potential as this data suggests.

CONCLUSIONS

Phosphorus loss must be measured considering total volume of leachate, or further, the soil mass in a leaching event. Phosphorus concentration did not show significant differences across sites nor leaching volumes, and will not indicate leaching differences though they may exist. For this reason, the use of P concentration to represent leaching loss should be used with caution. The bulk density of soils should also be considered if balancing per unit soil. Phosphorus losses reported as P leached per unit soil underestimates P loss for soils with higher bulk densities, such as sands. Phosphorus load is the best metric for measuring P leaching loss as a standard across multiple soil textures.

Phosphorus leaching potential is significantly influenced by initial STP level, soil type, and volume of leaching event. Like P loss through run-off, P leaching losses increase as initial STP level increases. This is likely due to the higher concentration of P in the soil solution in higher STP soils that is more susceptible to loss. Various soil physical properties influence the amount of P leaching loss as well. Leaching potential is greater in sandier soils, followed by silt loams and then clay loams, as shown in the volume study.

Existing soil P testing methods correlate with P leaching values and therefore, may predict P leaching with further correlation and calibration for Minnesota soils. The strongest indicator of P leaching loss is the volume of water in a leaching event. The rate of P leaching increases at a consistent rate across all soil types, indicating the volume of water in the leaching event determines P leaching loss. Further research is needed to confirm these results with leaching tests across a larger array of soil types with a greater range of leaching volumes.

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FIGURES

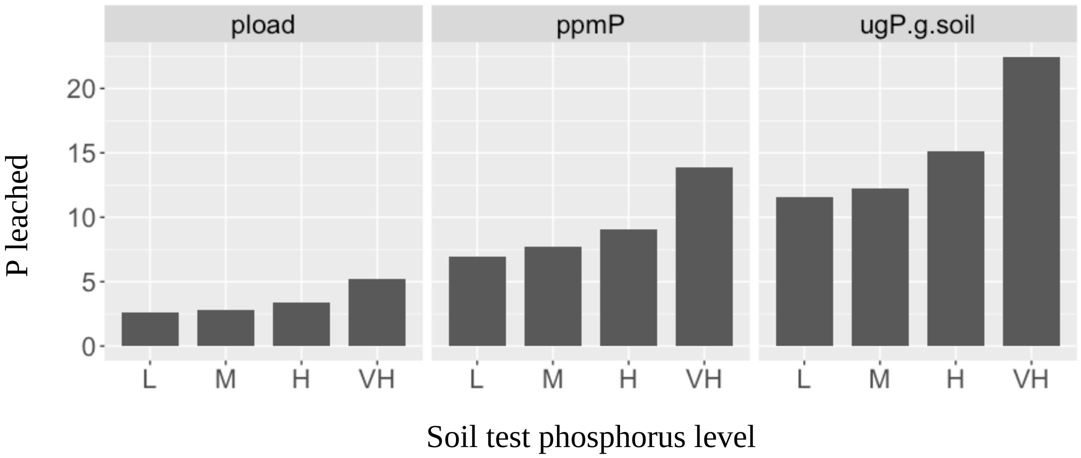

Figure 1. Phosphorus (P) leaching measurement averages across six Minnesota sites by initial soil test phosphorus (STP) levels [Low (L), Medium (M), High (H), Very High (VH)].

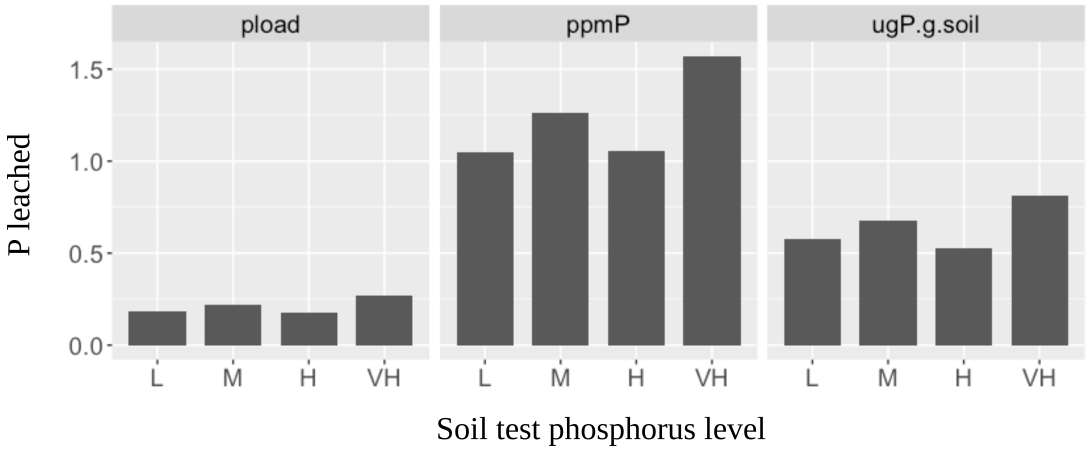

Figure 2. Comparison of phosphorus (P) leaching measurement averages by initial soil test phosphorus level (STP) [Low (L), Medium (M), High (H), Very High (VH)] for a sandy soil in Minnesota.

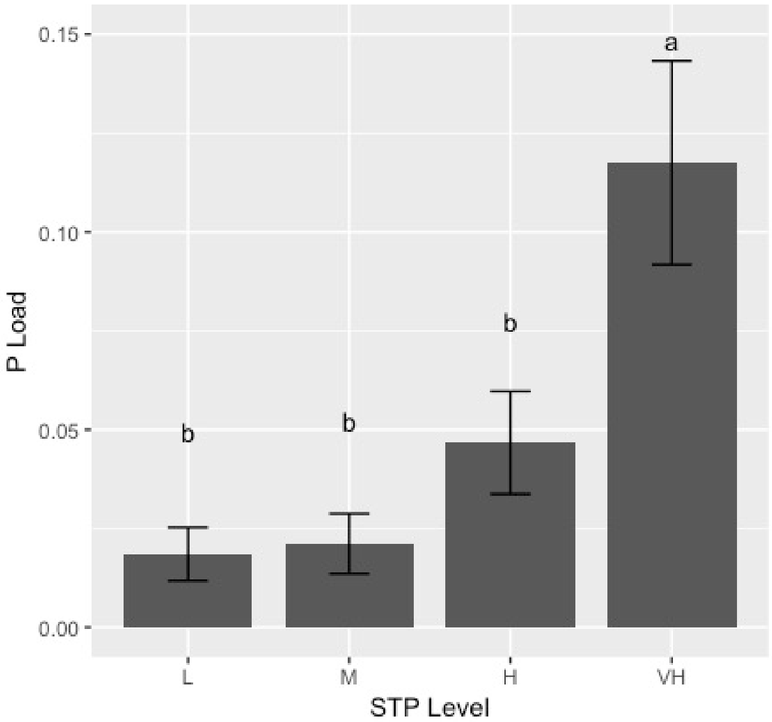

Figure 3. Average phosphorus (P) leachate loss as P Load for four soil test phosphorus (STP) [Low (L), Medium (M), High (H), Very High (VH)] levels at six Minnesota sites.

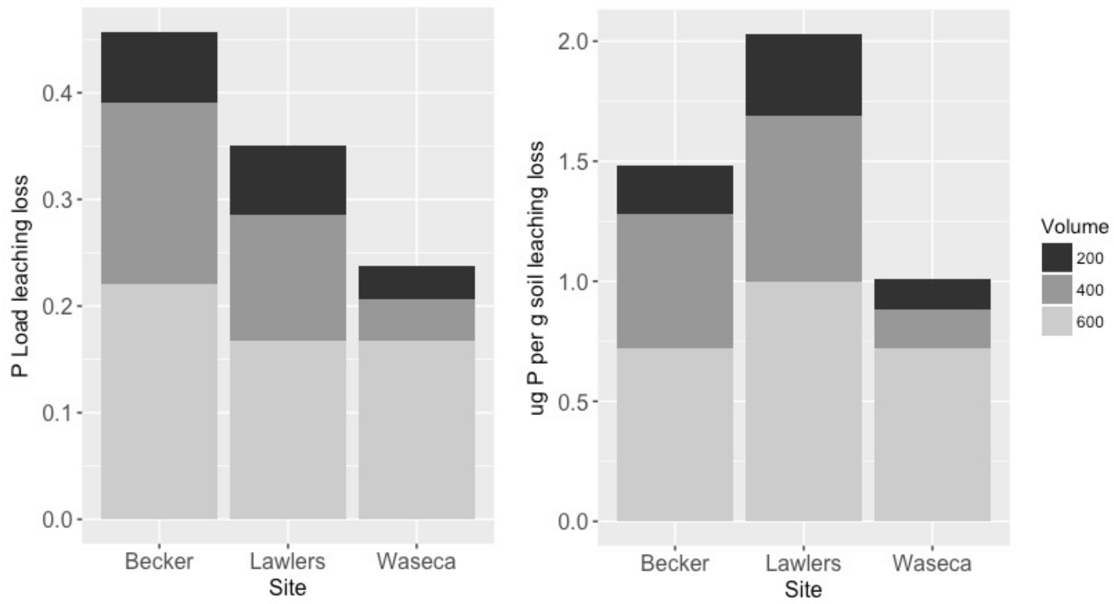

Figure 4. Comparison between two phosphorus leachate measurements, P Load and P leached per unit soil (µg P g soil^{-1}), for soil cores from three Minnesota soils leached at three volumes: 200mL, 400mL, and 600mL.

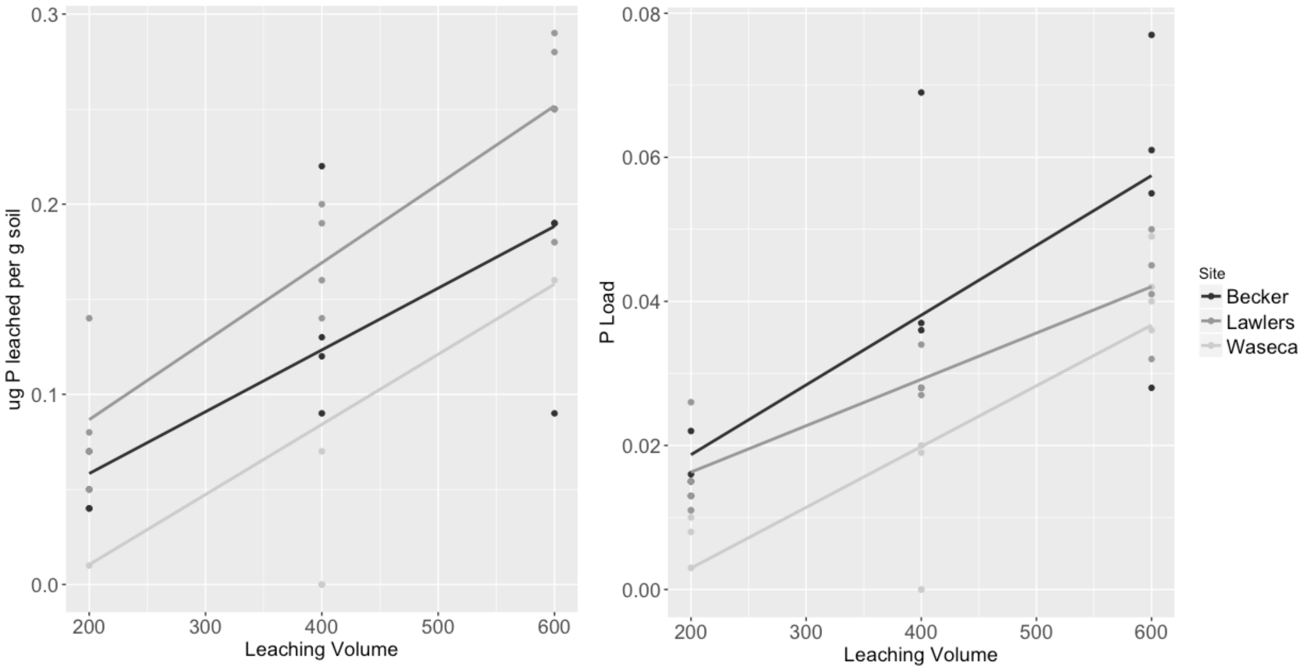

Figure 5. Rate of phosphorus leaching loss measured as P Load and P leached per unit soil (µg P g soil^{-1}) with increase of leaching volume for soil columns from three Minnesota sites.